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A STUDY OF FUNDAMENTAL FACTORS PERTINENT TO MICROBIOLOGICAL WASTE CONVERSION IN CONTROL OF ISOLATED ENVIRONMENTS

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UNIVERSITY OF CALIFORNIA
BERKELEY

Contract No. AF 19(628)-2462
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Task No. 865903
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FINAL REPORT

Period Covered: 1 March 1964 Thru 30 August 1966

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ABSTRACT

The report describes experiments concerned with the effect of various environmental factors on removal of algal nutrients, degree of waste treatment, and extent of water regeneration accomplished with the use of an algal-bacterial culture grown in a mechanically rotated culture vessel (algatron). The report also describes size and operational characteristics for a two-man environmental chamber, outlines basic characteristics for larger chambers in a space environment, and presents a design to support two men.

In basic biological studies the highest algal daily yield was 2.8 g (dry wt)/liter of culture. Total nitrogen removal ranged from 70% to 90%; NH_3-N, from 55% to 99%; PO_4, from 30% to 80%; Ca, from 17% to 70%; and Mg, from 0% to 13%. Extent of removal of PO_4 increased with increase in phosphate dosage. Removal of volatile dissolved solids ranged from 22% at a hydraulic detention period of 0.25 day to 38% at 1 day. Effluent BOD ranged from 14 mg/l at a BOD loading of 242 mg/l/day to 79 mg/l at a loading of 810 mg/l. From 87% to 91% of the incoming volatile solids were stabilized at detention periods ranging from 0.25 to 1 day. Rate of water evaporation from the algatron ranged from 1.83 ml/sq m/min at a relative humidity of 80% to 11.8 ml/sq m/min at a relative humidity of 45%. Accordingly, for solid and liquid waste treatment, approximately 0.038 sq m of drum wall area would be needed per kg of body weight.

A two-man ecological environmental chamber will require a 16-foot diameter by 16-foot high chamber, divided into two compartments of equal volume--a living compartment and a regeneration compartment. Within the regeneration compartment the number of algatrons required will probably not be less than 6 or more than 11 for each man. The 16-foot by 16-foot chamber has sufficient room for 22 algatrons, and hence may support 2 or 3 men during long-term isolation. The system will completely regenerate the atmosphere and reflux up to 12 gallons (45.42 liters) of water per man per day. A design concept for larger manned stations would involve horizontally rotating algatrons with axis of rotation parallel to a line

from the illumination source to the algatrons. This orientation would permit continuous illumination in a space configuration.

Studies on the effect of geometry of light source on algal growth led to the development of a novel lightweight culture system, the algatron system. The distinctive feature of the system is the culture of algae and associated bacteria as a thin film on the wall of a mechanically rotated transparent drum. An effective mixing and a high rate of internal recirculation is accomplished in the system by the insertion of a suitably designed probe and appropriate tubing. The system can be converted to a continuous mode of operation by the installation of a decanting probe and an injection device. The algatron system in various versions was used in the studies on waste treatment during the three years of study.

Highest daily algal yield with any of the four versions of the algatron used during the course of our studies was 2.8 grams (dry wt) /liter of culture. In studies on removal of algal nutrients (2nd year of research), extent of phosphorus removal increased with increase in phosphorus concentration of the medium, ranging from 34 mg/l at a PO_4 concentration of 46 mg/l to 9 mg/l at a medium concentration of 25 mg/l. In experiments with a newer model of the algatron (3rd year of research) but under less favorable growth conditions, only 30% of the incoming PO_4 was removed. Depending upon environmental conditions as well as upon the model of the algatron employed, total nitrogen reduction in concentration ranged from 70% to 98%; NH_3-N, from 55% to 99%. From 17% to as much as 70% of the incoming Ca was removed, depending again upon the type of algatron used and the environmental conditions. Very little Mg removal occurred under any of the conditions applied in the studies.

In the studies on waste treatment, loadings of feces and urine suspended in sewage were applied that ranged in BOD values from 242 mg/l to 810 mg/l. The BOD of the effluent ranged from 14 mg/l at the lower loading to 79 mg/l at the higher. Removal of total dissolved solids ranged from 22% to 38% at hydraulic detention periods from 0.25 to 1 day, and biomass detention periods from 1.7 to 6.1 days. Greatest reduction (38%) was at a 0.5-day hydraulic detention period and a 3.0-day biomass detention period.

Water evaporation from the algatron ranged from 1.83 ml/sq m/min with the unit sealed in a capsule (ambient relative humidity, 80%) to

11.8 ml/sq m/min with the unit in the open (relative humidity from 45% to 60%).

During the course of the 3-year contract period, the microterella design was further refined and the unit was made completely portable except for power source by installing it in a relay rack. The unit was equipped with an algatron in the third year of the period. In studies during the third year on effect of detention period and urea additive concentration on algal yield in an algatron when functioning as a component of the microterella, permissible urea dosage was found to be less with the algatron system (100-150 mg/l of medium) than it was with a conventional batch type culture (250-300 mg/l of medium). A maximum yield of 2.8 g/l/day was attained at a detention period of 0.75 day, urea dosage of 100 mg/l of medium. This maximum yield was 12% greater than that obtained with the batch type of culture system. In addition to the genetic factors, light apparently was a limiting factor in the study, since the algal concentration of the culture was almost the same at the 0.75 and 1-day detention periods; the yield, of course, was lower at the latter period.

The studies completed clearly indicate that through a combination of biological and physical systems fitted together in proper scale, it should be possible to regenerate air and water indefinitely in a manned isolated system utilizing sunlight as the primary source of energy. Food, however, will be a limiting factor because algae can only be utilized to a limited extent as a food for man, particularly when grown directly in his wastes. Thus, it is concluded that nonregenerative food must be supplied to man in such a system. For voyages of lengths forecast for the foreseeable future, about one pound of dehydrated food per day per man should be sufficient to meet his basic dietary needs. The nitrogen content of one man's food will be about 20 grams, whereas the nitrogen content of algae produced to meet one man's daily oxygen requirement will be about 40 grams. Thus, a deficit in nitrogen between human diet and algae is about 20 grams of N per day. This deficit must be made up as supplementary nitrogen to the algal cultures. At 20 grams per day the supplementary nitrogen requirement would be about 20 pounds per man per year. Similar calculations indicate that about two pounds of phosphorus and perhaps one pound of trace minerals would also be

required to supplement human sewage as a nutrient for algae in order to maintain an efficient regenerative culture. Thus, about 400 pounds of dehydrated foods and mineral supplements will be required per man-year. As these substances are utilized, dehydrated algae will be produced in the system and stored in place of the food and supplements consumed.

Because of the favorable results stemming from this contract work, the University of California has independently undertaken the task of actually constructing a full-scale manned ecological system patterned after the microterella. The system will be completed in early 1968. In it two men will be supported as indicated above in simulated voyages of increasing durations. Microbiological regeneration of their wastes into oxygen and potable water will be studied in detail as will their nutritional and other physiological and psychological requirements. Results of studies which will be made with this closed regenerative system will be highly pertinent to long-term life support in lunar bases or in permanently manned orbited stations.

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1. INTRODUCTION

1.1 Resumé of First Two Years of Research

a. First Year. Work during the first year of the research was concerned with: 1) a determination of optimum conditions for algal growth, primarily with respect to geometry of light source; 2) the design and operation of a specialized waste unit to obtain maximum waste treatment per unit of weight and volume of culture; and 3) the development and operation of an advanced model of the microterella to be followed by an investigation concerned with the capacity of the system

Studies on the effects of the geometry of the light source on algal growth showed that a bilateral-alternate arrangement of light source (150-watt reflector flood incandescent lamps) is more suited to algal growth than are the bilateral-opposite and unilateral arrangements. Average yields of 610 to 690 mg/l/day were obtained with the bilateral-alternate arrangement. Some evidence of light damage was noted, in that the chlorophyl content of the cells was only 0.87 percent. Average yields with the bilateral-opposite arrangement were from 510 to 605 mg/l/day, and the chlorophyl content of the cells was 1.22 percent. With the unilateral arrangement, the yields were from 513 to 598 mg/l/day, and the chlorophyl content of the cells was 1.74 percent.

In line with the search for means of increasing the efficient use of light energy by the photosynthetic member of the algal-bacterial symbiotic culture, it became obvious that a drastic departure in design from the concept of the conventional growth unit would have to be made. The ideal design would have to be simple in construction and operation, preferably should function independently of gravity, provide a thin film culture with a minimum of hardware, permit full-scale gas exchange, and allow for bilateral illumination. Confinement of culture between glass or plastic walls as is done in conventional units to accomplish depth control, illumination, and mixing involves great difficulty in keeping the confining walls sufficiently clean to permit the unimpeded entry of light, in aerating the culture to bring about gas exchange, and in cooling the cultures so as to maintain a proper thermal environment. The use of

a double-walled vessel also results in a high ratio of growth unit to active culture weight.

The search for the ideal culture system led to the development of the "algatron" system, namely one in which a culture is grown in a mechanically rotated transparent drum. Since a detailed description and discussion of the principles involved in the design and operation of an algatron system were presented in detail in the first technical report [1], only a brief description of the more important features is given at this time. As the drum rotates the frictional drag of its wall on the culture imparts a rotation to the culture that is essentially equal to its own. Under the applied forces, the culture suspension flows out of a reservoir and spreads as a vertical sheet upon the inside of the rotating drum. The algatron is operated as a chemostat by the installation of influent injecting and effluent decanting devices. The influent system can consist of any suitable injection mechanism. The effluent system preferably should be a decanting scoop positioned so that the distance from the drum wall is equal to that of the depth of the culture when it has reached the desired volume. Any injection of media that would cause the depth to exceed the clearance between the scoop and wall results in the removal of the excess liquid. Effective mixing is accomplished by placing a probe in the path of the rotating liquid. The introduction of the probe creates a wake in which turbulent mixing occurs and thus brings about rapid and continuous renewal of the culture surface and consequent gas exchange between culture and ambient atmosphere.

The principles of the design and operation of a horizontally oriented algatron are much the same as those for a vertical system. The chief differences would be those concerned with the vertical climb of the liquid and the reservoir design.

Experiments with the algatron system during the first year were confined to the use of a preliminary model. This prototype resulted in a maximum daily yield of 2.255 g of algae/liter.

Studies on waste treatment consisted in a continuation of studies begun under previous contracts on the use of a system which consisted of a specially designed algae growth unit and an activated sludge unit acting

in tandem [2,3], the operation of which was based on the differential settling characteristics of algae and bacterial sludge. As in previous studies involving the application of the same principle, sludge transport proved to be a problem. However, a maximum total dissolved solids destruction rate of 0.960 g/l/day was obtained. The studies on waste treatment were extended to include a determination of the feasibility of removing by electrodialysis the dissolved solids remaining in an algal culture medium after the algae had been removed. Estimates made on the basis of the studies indicate that the power required to remove salts not eliminated in the biological waste treatment system would be from 1.8 to 2.4 kw-hr/day/10 men.

During the course of the first year, a new model of the microterella was constructed in which refinements of previous designs [2,3] were incorporated. The new model was installed in a relay rack containing all of the ancillary equipment needed to make the unit completely portable and independent of any fixed utilities except power. Experimentation with the unit was concerned with making a determination of the effects of temperature variations of the culture, living quarters, and coil on the amount and rate of formation of condensate. At temperature conditions suited for optimum growth of the algae (30° to 32°C) and comfort for the crew (23° to 24°C), and a cooling coil temperature of 10°C, a yield of about 5 liters per square meter of cooling coil surface per day was obtained. However, the relative humidity in the living quarters was on the order of 65 percent. The latter could have been lowered by reducing the temperature of the cooling coil.

b. Second Year. Subjects of study during the second year of research were: 1) the determination of the combination of environmental factors needed for bringing about the most efficient functioning of the algatron and the microterella systems with respect to gas exchange, waste disposal and treatment, and water exchange; and 2) the preliminary design of a unit in which two 70-kg men could be made a part of a closed environmental system.

In experiments involving the algatron, and in which the effect of various environmental factors on yield was determined, maximum production (1.5 g/l/day) was obtained when the detention period of the biomass was

0.97 day, and that of the liquid phase, 0.75 day. Inasmuch as yield continued to increase as light energy flux was increased, the limiting factor with respect to yield was light energy flux. (Maximum light intensities at the inner and outer surfaces of the culture that could be attained with the lighting arrangment were 270 and 225 ft-c, respectively.)

No difference was observed in amount of yield under identical combinations of environmental factors when either Oscillatoria sp. or Chlorella sp. constituted the most abundant organisms.

As measured by BOD reduction and increase in stability of volatile dissolved solids, from 87 to 91 percent of the influent unstable dissolved solids was stabilized in a single pass through the algatron system at a liquid detention period as short as 0.25 day. The uniformly high rates of BOD reduction and increase in stability obtained at all of the liquid detention periods tried in the study (0.25 to 1 day) indicate that the detention period could be reduced to less than 0.25 day. Within the range tried, 1.7 to 6.1 days, no difference in stabilization rates could be attributed to biomass detention period.

Within the range of the experimental conditions applied in the study, the principal factor affecting the removal or loss of P, Mg, and Ca was the extent to which the influent concentration of these elements exceeded that needed for growth of the algal cells. The greater the excess, the greater was the loss due to precipitation or to causes other than assimilation. Therefore, the efficient use of these elements requires that they be added to the nutrient medium in amounts approximating those anticipated as being needed for full algal growth. At short biomass detention periods, the initial concentration of ammonia-nitrogen seems to be more decisive in determining the extent of removal than does detention period of biomass or of liquid. Except at the 6.1-day biomass detention period, all of the removal of nitrogen could be accounted for by that in the algal cells, assuming a nitrogen content of 7 to 8 percent in the cells. Only 52 percent of the removed nitrogen could be accounted for when the biomass detention period was 6.1 days. The unaccounted for fraction may have been lost as a result of volatilization.

The experiments on water exchange were done with the algatron sealed in an illumination sphere [4]. At the highest applied light energy flux, the rate of water recovery was 1.93 ml/sq m of wall surface. Rate of water loss, as judged by rate of recovery, was higher from an algal suspension than from water (containing nutrient salts in a concentration identical with that in the algal suspension) under any of the applied conditions. This difference cannot be attributed to their viscosities, since they were identical in that respect. At a low light energy flux, rate of water loss from a carbon black suspension was less than that from the algal suspension and from water only. However, at the highest applied light energy flux, rate of water loss from the carbon black suspension equaled that from the algal suspension and surpassed that from water alone. The lower rate of water loss at a lower light energy flux was due to the greater viscosity of the carbon black suspension--about 31 percent greater than that of the algal suspension and of water alone.

Essential components in a preliminary design of a two-man (70 kg each) capsule for long-term life support were established as being 1.2 lb/day of material in the form of dehydrated food and minerals, lavatory facilities, a 10-gallon waste liquefier, twenty-two 18 inch x 48 inch algatrons and associated illumination systems, a 30 sq m condensing system, and necessary fans to provide air transport for CO_2, O_2, and water vapor. The atmosphere of the system was to be maintained at 21% oxygen and 80% nitrogen on earth or, theoretically, 40% oxygen and 60% nitrogen in space. Details of the characteristics of the designed system, parameters established for attaining environmental control, and design elements of the system were described in the second technical report [4].

1.2 Scope of the Investigation

The work summarized in section 1.1 and that done during the third year of research were conducted in accordance with a plan of study designed to attain the objectives listed in the first and second annual reports and the following: 1) Determination of the extent of gas exchange, waste disposal and treatment, and other reclamation rates that are attainable in the microterella and algatron systems as influenced by: a) retention period of culture, b) light intensity, c) buildup of decomposition

resistant organic constituents in the system, d) ratio of algal-bacterial culture weight to weight of supported animals. 2) Determination of the minimum weight and energy requirements of the microterella systems components. 3) Using the microterella and algatron systems as bases, continuation of work on the design of a unit in which two 70-kg men would be a part of a closed environmental system.

Attempts were made to study the composition of the reclaimed water with respect to Cu, Fe, and Cr, and toxic materials. Procedures reported in Standard Methods 12th ed. and Official Methods of the Assoc. of Official Agricultural Chemists, 9th ed. were tried. The attempts proved unsuccessful because of the highly complex materials occurring in these waters.

The major part of the effort during the third year of the contract period was spent in developing procedures for maintaining highly concentrated symbiotic (algae and bacteria) biomass in the algatron under conditions permitting the application of very heavy loadings at very short detention periods with a minimum volume and weight of liquid within the reactor.

Studies on the use of highly concentrated biomass and short detention periods were conducted with the use of the algatron of the model described in the second annual report. During the third year, further studies were made on improving the design of the algatron. As a part of these studies, two tall vertical models powered in tandem, and a horizontal model were constructed. The two vertical models were used in studies on the removal of algal nutrients from waste water and on yield of algae; the horizontal model was used in reaeration studies. Toward the end of the second year, an algatron was installed in the microterella. Because of the degree of miniaturization necessitated by the small physical dimensions of the microterella unit, operational difficulties were unavoidable. The early part of the third year was spent in developing methods for minimizing the difficulties. Studies were conducted on the effect of the key environmental factors, detention period, and light on the yield of algae and the oxygen production in the microterella.

During the third year, the design of a two-man unit was advanced to include the size and configuration of the reflux condensation and waste treatment units.

1.3 Conduct of the Investigation

The investigative work reported herein was carried on during the period 1 March 1965 to 1 August 1966 by the Sanitary Engineering Research Laboratory of the University of California, Berkeley under contract AF 19(628)-2462 between the Air Force Cambridge Research Laboratories, Office of Aerospace Research and The Regents of the University of California.

2. MICROTERELLA

2.1 Modifications

The microterella complex used in the investigations during the third year of the research period was the one described in the 1964-65 report [4]. The installation of an algatron in the microterella complex (cf. Ref. [4]) necessitated a number of modifications of the algal-bacterial culture system prior to instituting an experimental program.

Because of the centrifugal field set up by the rotation of the algatron, algal cells collected on the wall of the unit. By means of a timer inserted into the system, the algatron was inactivated for a 5-minute period each hour. As the algatron came to rest, the culture would descend to the bottom of the unit, carrying with it cells deposited on the algatron wall. The frequency of the stops prevented any film from adhering to the wall.

As originally designed and described in the 1964-65 report, the mixing probe was intended to serve a threefold function, viz., mixing, effluent discharge, and recirculation. However, the collecting port in the probe proved unreliable as an effluent discharge due to clogging. Consequently, another discharge system was substituted. The new system involved the use of a metering device (described in detail in the 1965-66 annual report [1]) in conjunction with a Sigma pump and effluent tube, so arranged as to dip into the culture only during the time it is at the bottom of the algatron during the 5-minute quiescent period. As the algatron came to its hourly pause, the Sigma pump was activated, pumping culture from the effluent intake to the metering device until a predetermined amount was collected. Then it stopped functioning. With such an arrangement, no gas was removed from the system, since the effluent intake was

submerged during the pumping period. Such an arrangment would not be required in a man-sized unit since the collecting opening in the mixing probe would be made large enough to preclude clogging.

2.2 Experiments

Experiments conducted with the use of the microterella were concerned with determining the effect of urea concentration, of detention period, and of light on the daily yield of algae in the system, and thereby on the life support capacity of the system with respect to mice.

a. Procedure. The trays were kept in position during the experimental runs. The detention period was generally held at one day but varied from 0.5 to 1.5 days in experiments on the effect of detention period length. The culture temperature remained at 30° to 32°C during all of the experiments. Four side lamps (150-watt, outdoor projector spot lamps) and one bottom lamp (500-watt, G.E. Quartzline lamp) were used as light sources. The effectiveness of the bottom light as an illumination source was determined by comparing the daily algal yields obtained with the bottom light off, with one on, and with two on. Sewage enriched with urea (100 mg/l) was used as the medium. In the experiments concerned with urea dosage, a synthetic medium (300 mg each of $MgSO_4 \cdot 7H_2O$ and KH_2PO_4 and 1 ml of Arnon's trace element solution [5] per liter of distilled water) was used. Dosage of urea was varied from 0 to 400 mg/l of medium injected into the culture.

b. Results. The effect of urea dosage on daily algal yield is indicated by the curve in Figure 1, in which average yield at each concentration is plotted as a function of urea concentration in the medium. Deviation from the average value ranged from +47 mg/l to -49 mg/l. Maximum yield was obtained when the detention period was 0.75 day, as is shown by the curve in Figure 2, in which daily algal yield is plotted as a function of length of detention period. Deviations from average values for culture concentrations in the experiments concerned with detention period ranged from -47 to +32 mg/l, except for those at the 0.75-day detention period, in which the range was from -103 to +90 mg/l. Daily yield in the absence of bottom illumination ranged from 1398 to 1478 mg/l and averaged 1442 mg/l. With two of the bottom lights functioning, the average daily yield increased to 2092 mg/l (range: 2002 to 2139 mg/l).

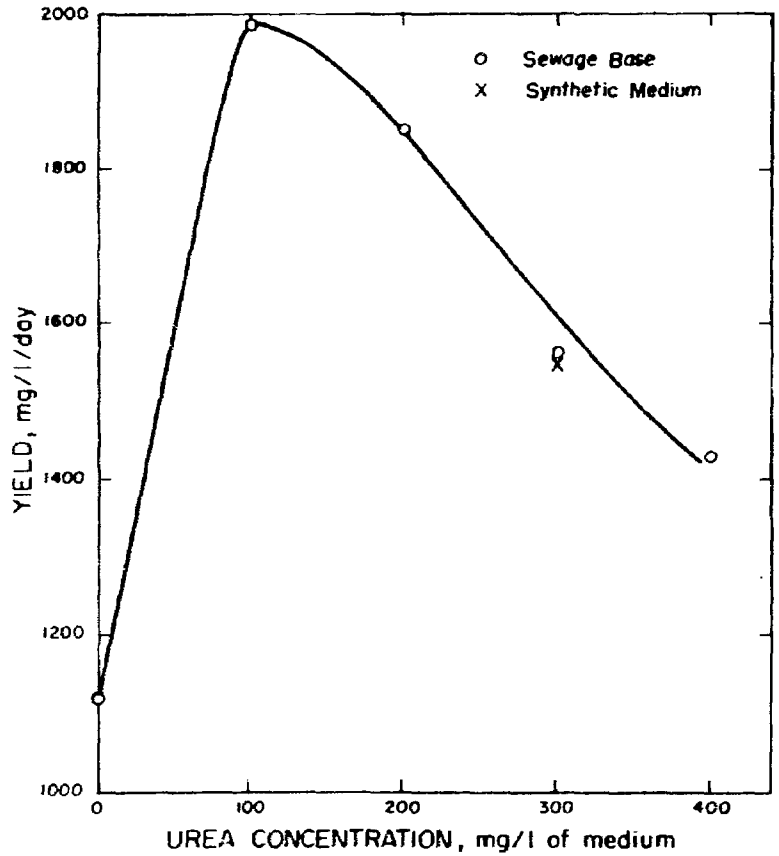

FIGURE 1. EFFECT OF UREA CONCENTRATION ON DAILY ALGAL YIELD IN THE ALGATRON

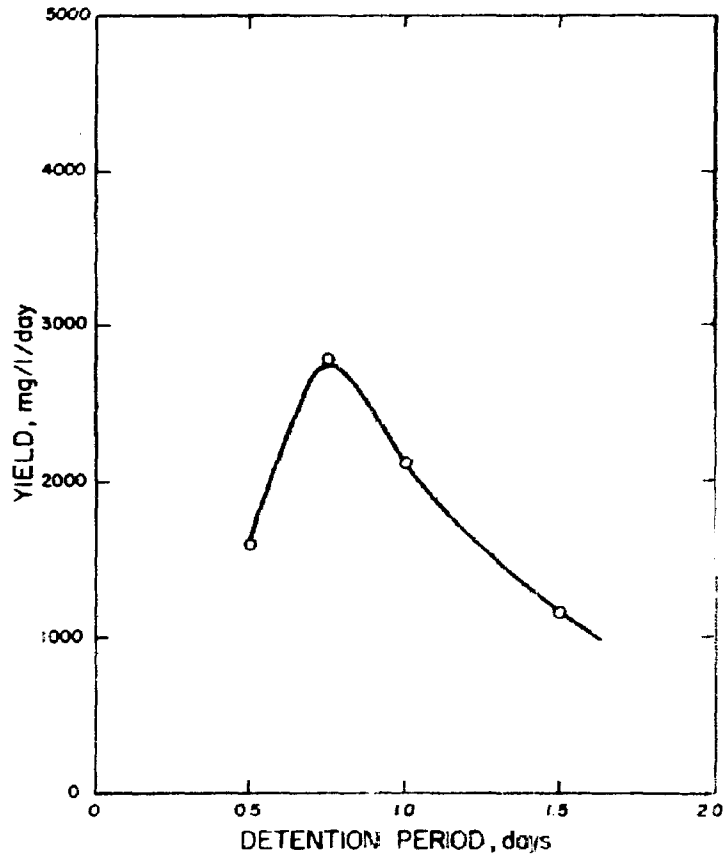

FIGURE 2. EFFECT OF DETENTION PERIOD ON DAILY ALGAL YIELD IN THE ALGATRON

The average daily yield dropped to 1981 mg/l upon the removal of one of the two bottom lamps. Range of yield in this case was from 1879 to 2043 mg/l.

c. Discussion. The experiments concerned with urea dosage showed that inhibition of algae growth occurs as the concentration of urea in the medium exceeds 100 mg/l. The permissible dosage of urea is lower when the algatron system of algae culture is used in the microterella than when a conventional batch-type system is used; since in the latter, urea concentrations in the medium as high as 300 mg/l resulted in no apparent adverse effects. The lower permissible concentration when an algatron is used may be due to an enhancement in rate and extent of decomposition of mouse wastes because of a more effective and complete gas exchange. The increased rate of breakdown may result in the production of ammonia-nitrogen at a rate faster than it can be assimilated by the algae. Consequently, a buildup of the compound may ensue when the concentration of urea is too great.

The drop in daily yield upon lengthening the detention period from 0.75 day to 1 day may be attributed to light becoming inhibitory rather than to an increase in age of cells and change in environment with increase in time. The culture concentration remained relatively constant during extension of the detention period. It averaged 2112 mg/l at the 1-day detention period and 2116 mg/l at the 0.75-day period.

Light remained a limiting factor even with the combination of the two bottom lamps and the side lamps supplying the illumination, despite the indications to the contrary given by the very small increase in yield upon increasing the number of bottom lamps from one to two. The failure to obtain a more substantial increase was due to lack of a means for deflecting the light into the culture. Consequently, large-scale increases in light output resulted in only very small increases in the amount of light actually reaching the culture. Illumination of the inner surface of the spinning culture was less than satisfactory.

The culture volume requirements per gram of mouse were reduced somewhat from those with the batch-type setup. On the basis of a 96-mg requirement of oxygen per gram of mouse per day, 60 mg of algae would have to be produced per gram of mouse per day. At the maximum daily

yield obtained with the algatron system in the microterella, viz., 2.8 g/l/day, the culture volume requirement would be 0.021 liter per gram of mouse. Since in experiments with the batch-type culture [2], the highest yield was 2.5 g/l/day, the volume requirement with such a growth system would be 0.024 liter of culture/gram of mouse.

3. ALGAE NUTRIENT REMOVAL

As a part of the research work, attempts were made to increase the efficiency of the algatron system by suitably altering the design of the unit. In line with this phase of the research, two new units were constructed, and experiments were conducted on algae nutrient removal. The two units were installed and tested in a semi-closed chamber.

3.1 Description of the New Algatron Units

Each of the two new units consists of an appropriately designed plexiglas cylinder 4 ft in height and 18 inches in diameter. A schematic diagram of the arrangement and the construction of the algatrons is shown in Figure 3. Mounting details for the units are shown in Figure 4 and construction and bearing assembly details are shown in Figure 5. A photograph of the installed units in operation is shown in Figure 6. As is evident in the photographs, the two units are powered by a common motor. Timing belts were used to impart the rotational force from the motor to drive gear of the individual units. The units were supported by bearings at the top and bottom of the cylinders.

As is indicated in Figures 3 and 4, the algatron cylinder has a series of plastic ledges (width 1 inch) installed at intervals (6 inches). Each is perforated at 4 equidistant points by three serially arranged holes, 1/4, 3/8, and 1/2 inches, respectively, from the wall of the cylinder. The ledges were installed to provide a more uniformly thick culture layer than would have been possible were no ledges present. As is to be expected, in the presence of a gravitational field, the culture in a rotating vertical cylinder would assume the configuration of a triangle in cross section, i.e., the culture would be deepest at the base of the cylinder, and shallowest at the top. In a cylinder 4 ft high, the base depth would be excessive and the top depth nonexistant. The insertion of the ledges

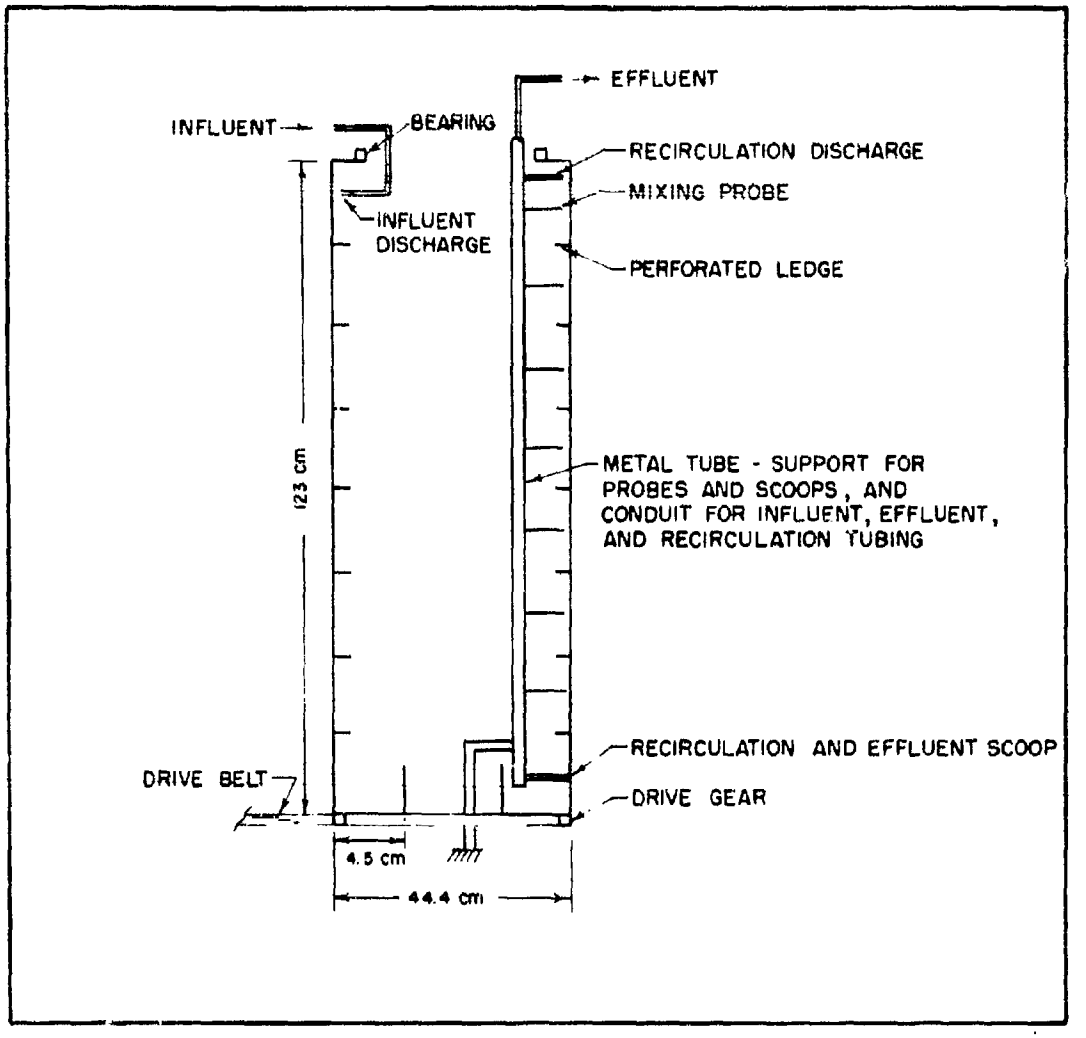

FIGURE 3. SCHEMATIC DIAGRAM OF THE 18 in. x 48 in. VERTICAL ALGATRON

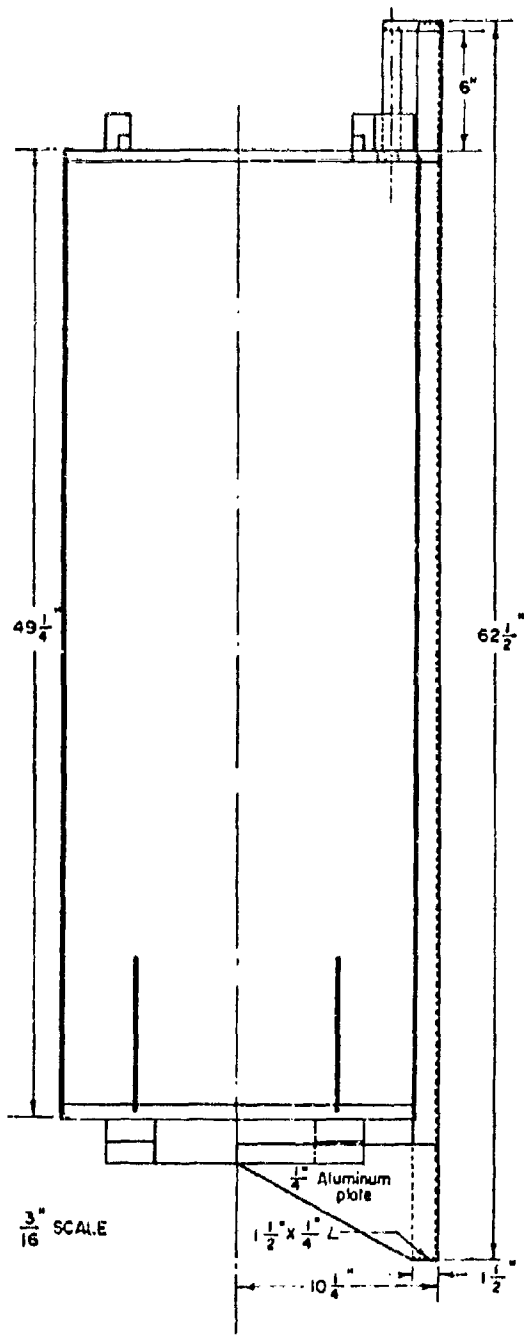

FIGURE 4. MOUNTING DETAILS FOR THE 18 in x 48 in VERTICAL ALGATRONS

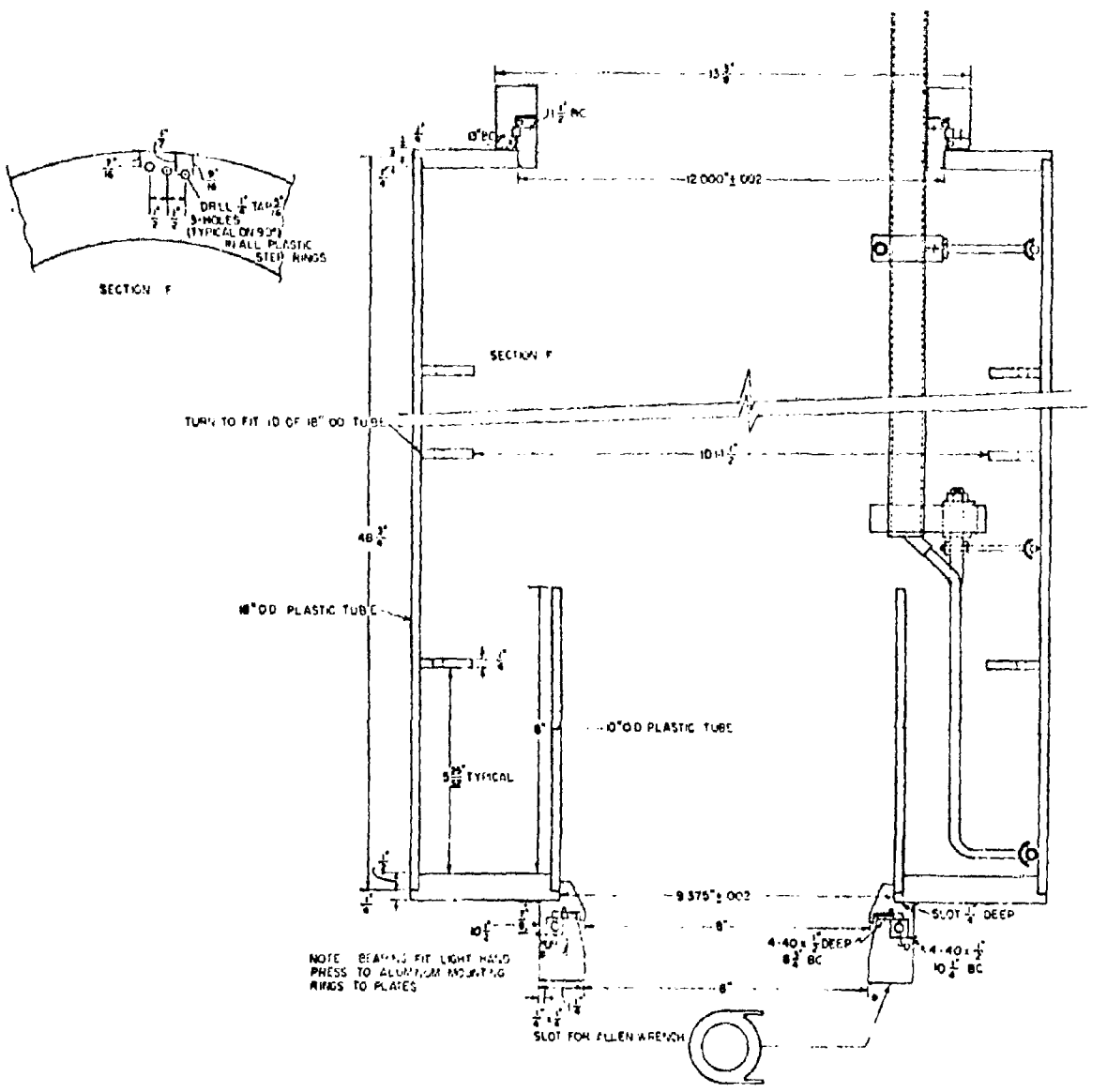

FIGURE 5. CONSTRUCTION AND BEARING ASSEMBLY DETAILS FOR THE 18 in. x 48 in. VERTICAL ALGATRONS

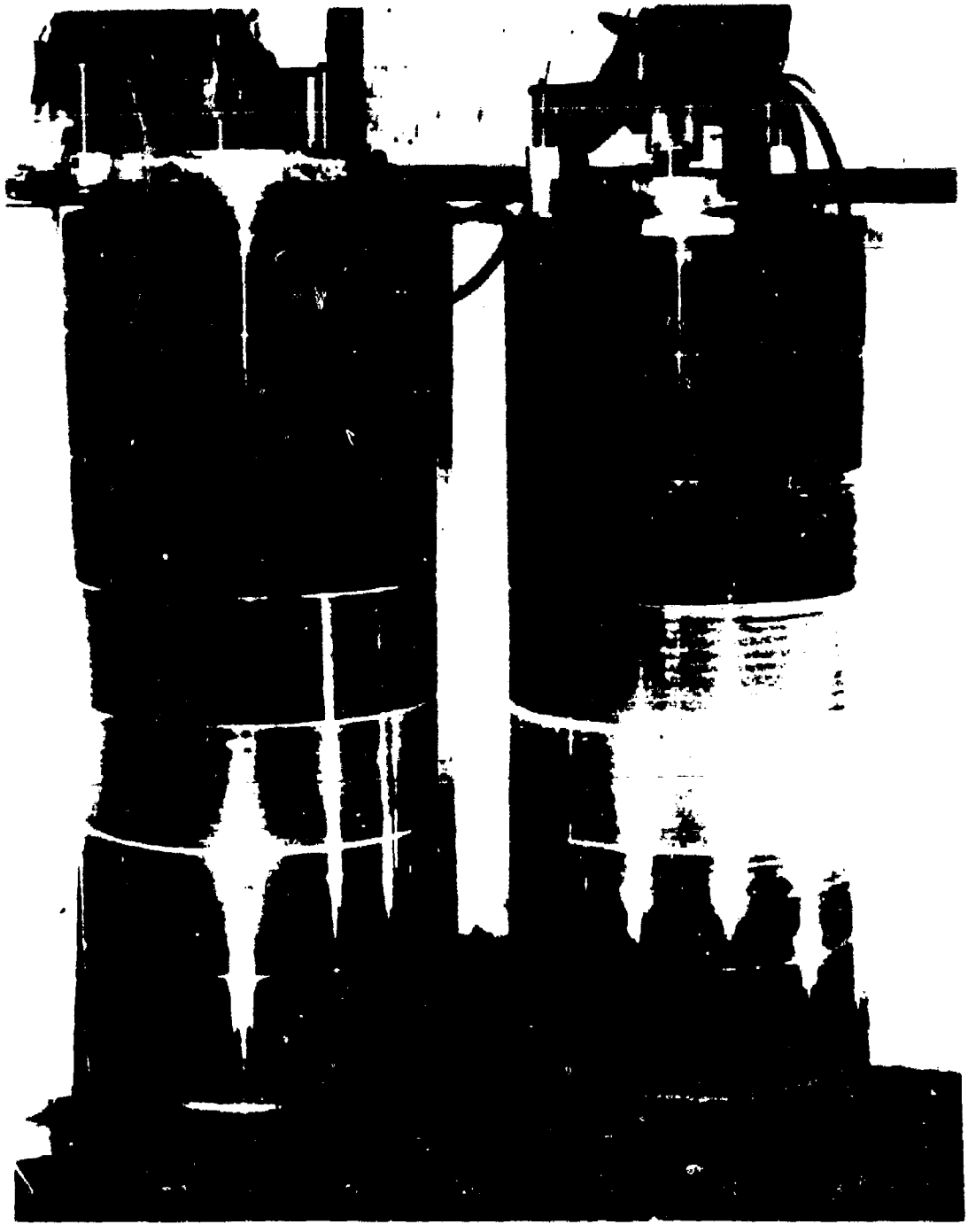

FIGURE 6 . NEW MODEL ALGATRONS OPERATING IN TANDEM

resulted in the formation of a series of small "triangles," and consequently a smaller difference between base and top depths. Moreover, by passing the liquid over a series of ledges, the travel time of the liquid through the algatron is better controlled and lengthened. The perforations in the ledges permit the liquid to flow from one level to the next. The base depth of the layers of culture in each section was determined by the distance of the first open perforation from the algatron wall.

The mixing, recirculation, and discharge probes, as well as the influent structure, were mounted on and in a stainless steel tube (cf. Figure 3).

The mixing probes consisted of strips of aluminum about 1/8 inch in diameter and 4 inches long. Each strip was bent about 1/2 inch from the tip to form a right angle hook. The curved portion of the hook was opposing the direction of the rotation of the layer of culture. The first type of recirculation scoop to be tried consisted of a piece of aluminum tubing (1/4 inch in diameter) shaped in such a manner that culture liquid would be channeled into it. Although it very effectively scooped up liquid, it soon was clogged by hair and other debris which were caught in the rough edges of the cut tubing. Probably the problem could have been overcome by carefully machining the cut end of the tubing. In the experiments described in this report, "streamlined" probes served as recirculation scoops.

The recirculation intake was at the base of the cylinder, and the discharge at the top. A "T" was inserted in the recirculation tube so that a part of the recirculating culture could be discharged from the system; and thus served as the effluent collecting and discharge device. The recirculating liquid that was discharged into the top layer of the cylinder slowly traveled to the bottom of the cylinder, i.e., through each ledge, and was again scooped up and introduced into the recirculation system.

The influent system consisted of a Sigma pump and tubing to and into the algatron. The discharge end of the feed tube was located at the second-from-the-top ledge of one algatron, and at the bottom section of the other by way of the recirculation scoop. Locating the influent discharge tube at a top level minimized short-circuiting of incoming nutrient to the effluent port, since the incoming feed had to travel to the bottom

of the cylinder before coming into contact with the recirculation-effluent system. The principal advantage of the second system was that the feed process served as a flushing device for the recirculation probe. The chief disadvantage was the proneness to short-circuiting. The Sigma pump was connected to a timing device so that the length of the feed injection period could be varied. Dosage was regulated by means of length of time per hour the pump was activated, diameter of tubing, and speed at which the pump was operated. A simple effluent regulation device was used. It consisted merely of restricting the flow from the units by means of a screw-type pinch clamp. The method proved satisfactory for the preliminary experiments that were performed.

3.2 Experiments

a. Methods. Experiments involving the use of the new units have been few in number, because they were only recently completed to the operational stage. The experiments were intended to determine the performance of the new units under minimal conditions. Conditions were perforce minimal because lighting was inadequate, and CO_2 concentration and rate of feed were lower than would be encountered under more "normal" conditions. One unit, designated "right" column, was ventilated by a "squirrel-cage" blower placed at the top of the cylinder. The other designated the "left" column was ventilated by convection. Judging from the comparative rates of evaporation, air flow through the "right" column was twice that through the "left" unit.

Illumination was accomplished by placing five 500-watt G.E. "Quartzline" (Iodine vapor) lamps in a semicircle in front of the two units (2-1/2 lamps per unit). A major disadvantage of the lighting arrangement was that the cultures could not be illuminated uniformly from top to bottom. For example, the light intensity ranged from 45 ft-candles at the top and bottom extremities of the cylinders to 600 ft-candles over a 6-inch band at a point midway up the cylinders and directly in line with a lamp. The lamps were placed approximately 3 feet from the cylinders. Because the units were mounted on a wall, about 1/3 of each cylinder was in the dark at a given instant. The cultures were not bilaterally illuminated.

In the experiments the input rate of the feed was adjusted for low effluent discharge and high liquid evaporative loss. The biomass was not harvested during the five-day period of each run. In fact, the algatrons were not shut down at any time during a 5-day run. As a result, a layer of algae was deposited on the cylinder wall. This layer increased in density as the run progressed, thus contributing to the light problem.

The culture volume in the "right" column was held at about 9.3 liters (its capacity was 26 liters), and that of the "left," at 10.6 liters (capacity, 26 liters).

As indicated by the above description, the principal differences between the two units were the manner and degree of ventilation and the method of feed injection.

b. Results. The "right" algatron culture had a loss of 2.25 liters in 5 days, whereas that of the "left" unit increased approximately 7 liters. As stated before, both units were fed at the same rate, and the rates of effluent discharge were approximately the same. The algal concentration in the "right" culture averaged 647 mg/l at the start, and 3120 mg/l at the end of 5 days (concentration adjusted on the basis of initial volume). Including algae discharge with the effluent, the daily yield per liter of culture averaged 600 mg/l/day. The initial concentration in the "left" column averaged 470 mg/l; and the final concentration, 1315 mg/l. Including discharged algae, the average daily yield from the unit was 350 mg/l/day. Two algal types constituted the predominant organisms, namely Chlorella and Oscillatoria. Oscillatoria surpassed Chlorella in abundance in the "left" unit; while the reverse was true in the "right" unit.

The higher average daily yield of algae from the right unit over that from the left is another indication of the possibility of CO_2 deficiency in the left. The greater degree of ventilation provided the right column assured a more abundant supply of CO_2. The yield was greater than that which could be obtained from conventional growth units under comparably unfavorable light conditions.

It should be noted that the effluent from both units always was devoid of algae by the fifth day. The average increase in total dissolved solids concentration was not as great as might be expected. An average

of 32 g (16 g/unit) of dissolved solids were fed the units during each five-day period. During each period, an average of 1.2 g were discharged from the "right" unit with the effluent; and 3.9 g from the "left" unit. The total amount of dissolved solids remaining in the culture in the "right" column averaged 4.9 g. On the basis of initial volume of the culture, the total dissolved solids concentration initially was 374 mg/l, and finally, 520 mg/l--an increase of 146 mg/l in concentration. The total amount of dissolved solids remaining in the "left" column averaged 7.3 g. On the basis of the initial volume, the dissolved solids concentration initially was 324 mg/l; and finally, 700 mg/l--a gain of 376 mg/l. The difference in rate of gain between the two columns could have been due to a variation in precipitation, a greater use of nutrient salt by the algae in the "right" column because of its greater algal yield, or a loss of liquid that may have been displaced by splashing.

Effluent discharged from the "right" unit had an average total dissolved solids concentration of 394 mg/l; and that from the "left" unit, 320 mg/l.

An average of 7 g of dissolved volatile solids were fed each unit during a 5-day period. The initial volatile dissolved solids concentration of the culture in the "right" unit averaged 150 mg/l; and its final concentration, 148 mg/l. Apparently, very little buildup of volatile dissolved solids occurred in the unit. The initial volatile dissolved solids concentration in the "left" unit was 125 mg/l; and its final, 155 mg/l. Thus, a buildup of 30 mg/l occurred in this unit.

The final dissolved volatile solids of the effluent from the "right" unit averaged 107 mg/l; and that from the "left" unit, 85 mg/l.

An average of 4.7 g of total nitrogen were fed each unit during a 5-day period. Of this, 2.3 g (or 50%) could be accounted for by the algae produced by the "right" unit. Algal production also accounted for 50% of the incoming total nitrogen in the "left" column. The total nitrogen concentration of the final effluent from the "right" column was 31 mg/l; and that from the "left"unit, 23 mg/l. The influent concentration averaged 107 mg/l. The NH_3-N concentration of the influent averaged 51 mg/l; that of the "right" unit's final effluent, 4 mg/l; and that of the "left" unit's final effluent, 19 mg/l. The organic nitrogen

concentration of the influent averaged 56 mg/l; that of the "right" unit's final effluent, 23 mg/l; and that of the "left" unit's final effluent, 9 mg/l.

The average concentrations of calcium, magnesium, and phosphate are listed in Table I.

TABLE I

AVERAGE CONCENTRATIONS OF CALCIUM, MAGNESIUM, AND PHOSPHATE

Item	Ca (mg/l)	Mg (mg/l)	PO_4 (mg/l)
Right Unit Centrifuged Supernatant	9	26	13
Left Unit Centrifuged Supernatant	18	29	37
Right Unit Final Effluent	8	39	7
Left Unit Final Effluent	17	31	7
Influent	29	33	15

According to the table, a considerable buildup was taking place within the cultures, or on the drum walls, since the PO_4 discharged with the effluent from the cultures was only about 50% that of the influent.

c. Discussion. Despite the unfavorable illumination arrangement, approximately 70% of the incoming total nitrogen and about 85% of the NH_3-N were removed. About 70% of the removed nitrogen could be accounted for as new algal cellular material. The rest could have been lost through volatilization as NH_3-N or it could be only an apparent loss because of experimental error made in the analytical procedures. The fact that the phosphate content of the centrifuged supernatant was higher than that of the final effluent may have been due to the formation of colloidal particles having a density not great enough to permit concentration by the centrifugation applied in the analytical procedures, but yet sufficiently great to permit a buildup during the longer exposure time in the centrifugal field set up by the spinning algatron. Because of the absence of short-circuiting and the comparatively long time required for a given substance to travel from the influent port to the effluent discharge, colloidal

particles not dense enough to be separated by the 10-minute centrifugation (500 x g) applied in preparing a sample for analysis, would nevertheless be retained in the algatron column.

The principal disadvantage of the new model was the difficulty in gaining access to the lower reaches of the interior of the column because of the narrow diameter of the column in relation to its height. The columns were limited to 18 inches in diameter. The 4-foot height of the units was based on the required area to attain one-tenth the gas exchange capacity required for one man.

4. WASTE TREATMENT - SYSTEM OF PRETREATMENT AND ALGATRON

The investigation on the use of the algatron for the treatment of solid and liquid body wastes from humans was started by establishing a system in which the wastes would receive a certain amount of pretreatment before being introduced into the algatron. This was accomplished by connecting a differential settling type of unit to the algatron system. This differential settling type unit was used in previous experiments on waste treatment and has been described in detail in previous reports [2,3]. Such a unit consists of two chambers, one in which the contents are kept in motion and a second in which they are maintained in a quiescent condition. Algal suspension enters the unit by way of the agitated chamber and leaves from the quiescent chamber. In operation algal suspension scooped up by the mixing probe in the algatron is forced through the differential settling unit by the energy imparted by the rotational movement of the algatron. Overflow from the differential settling unit is channeled back to the algatron by gravitation. Thus, no additional energy was required for the operation of the differential settling unit.

Feces, blended with settled sewage in a Waring blender, and the algal suspension from the algatron were introduced into the active chamber of the differential settling unit. The detention time of liquid passing through the differential settling unit was 40 minutes. Urine entered the algatron directly as part of the liquid medium fed the unit during the course of the day. Detention period in the algatron was 1 day. In theory, the algal suspension should have passed through the active and quiescent chambers without loss of algae; while the heavier bacterial floc and fecal

particles should have settled to the l n c the quiescent chamber and gradually worked back to the active cha. In practice there was a considerable loss of bacterial floc and fec particles from the differential settling unit into the algatron.

Only one loading rate was tried, namely, 2.1 g (dry wt) feces and 74 ml urine per liter per day. In terms of BOD, that coming from the sewage and urine mixture ranged from 725 to 839 mg/l. The addition of feces brought the BOD loading to 875 to 1060 mg/l. Depending upon loading, the effluent BOD ranged from a low of 1 mg/l to as high as 105 mg/l. The algal concentration in the algatron varied from 975 mg/l to 1475 mg/l. Odors ranged from negligible to a pronounced urine smell.

There was a wide variation in quality of the effluent due to factors other than loading. The mixing probe became clogged and interrupted recycling of algal suspension through the differential settling unit. Hence no dissolved oxygen was available to the bacterial population in the unit. There was a cessation of waste treatment, a high BOD in the effluent, and the presence of a strong urine odor. Clogging would not necessarily be a factor in a full-scale system, since the influent port in the mixing probe of the algatron could be made much longer than was possible in the present installation. There was also a loss of bacterial floc and fecal particles from the differential settling unit to the algatron, resulting in an increase in turbidity of the algal culture in the algatron.

5. WASTE TREATMENT - SYSTEM INVOLVING AN ACCELERATED BIOMASS IN AN ALGATRON

5.1 Introduction

The aims of the series of experiments described in this section were as follows: 1) In general: a) Determine the capacity of the photosynthetic reactor in its function in the algatron as a part of an integrated biological system with respect to waste treatment, algae nutrient removal, water production, and oxygen supply. b) Investigate the overall functioning of the algatron at relatively high organic loadings and short detention periods. 2) In particular: a) Evaluate the potential of the

accelerated symbiotic biomass-algatron system in BOD (biochemical oxygen demand) reduction (i.e., conversion) and algae nutrient utilization in situations in which human wastes are treated under space conditions. b) Determine quantitatively the extent of water regeneration (low temperature distilled water production) that can be expected with the use of the algatron system. c) Estimate the advantages resulting from the use of a dense algal-bacterial symbiotic biomass culture as a means of obtaining maximum BOD and nutrient reduction, as well as oxygen production and carbon dioxide absorption per unit of weight, volume, and surface area of the reactor. d) Devise and evaluate methods of applying the separation of biomass and the recirculation of a portion of the concentrated biomass slurry as a means of maintaining a relatively high concentration of reactor biomass even at heavy hydraulic loadings, i.e., providing long biological and short hydraulic detention periods. e) Increase light conversion efficiency of the algae by applying controlled internal mixing and recirculation to enhance substrate-biomass mixing and provide an optimum light periodicity.

The algatron model used in these studies, and which was described in our previous reports, was modified as shown in Figure 7. Important dimensions of the unit are given in Table II.

5.2 Operation

a. Internal Recirculation. To provide internal recirculation of the culture, the mixing probe (Figure 7, item 12) was set so that 1.5 liters of culture/min were discharged into the internal recirculation system (Figure 7, item 11) at a point 15 cm from the bottom of the drum, and thus it provided a recirculation mixing ratio of 18 liters recirculated culture per hour per liter of reactor (culture) volume, or 432 l/liter-day. The influent was injected into the recirculation system prior to redischarge into the culture. No added source of power was needed for the internal recirculation since the latter was operated by the rotation of the drum.

Internal recirculation served a sixfold purpose: 1) It ensured continuous contact between substrate and biomass. 2) It brought about continuous surface renewal. 3) It dissipated odors of the strong influent. 4) It equalized exposure of the light to the biomass and brought about a light periodicity with respect to the individual algal cells. 5) It

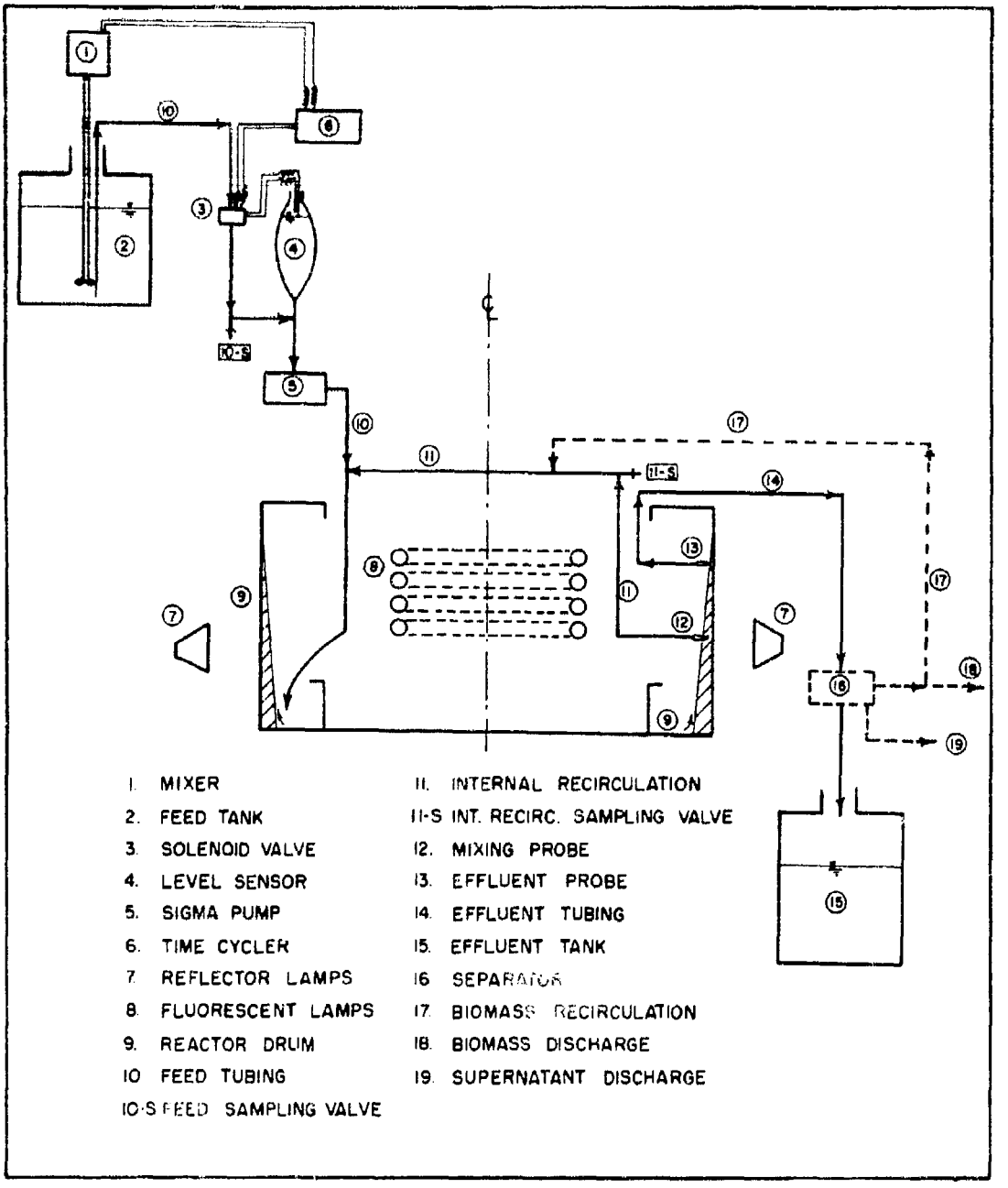

FIGURE 7. ALGATRON SYSTEM USED IN SOLID AND LIQUID WASTE TREATMENT

TABLE II

IMPORTANT DIMENSIONS OF VARIOUS COMPONENTS IN THE ALGATRON USED IN SOLID AND LIQUID WASTE TREATMENT

(24 in. Diameter x 12 in. Height)

Component	Dimensions	
Algatron Drum	Diameter	61 cm
	Radius	30.5 cm
	Height	30.5 cm
	rpm	240
Culture (film)	Height	24.13 cm
(film)	Surface	4620.0 cm^2
(average)	Depth	10.8 mm
(approx. max)	Depth	21.6 mm
	Volume	5.0 l
Radial Acceleration		20 x g
Specific Liquid-Air Surface[a]		0.924 cm^{-1} $\frac{cm^2}{cm^3}$
Mixing Probe	Position	15.2 cm from base of drum, and 1.5 mm from drum wall.
Effluent Probe	Position	19.5 cm from base of drum, and 3.0 mm from drum wall.

[a]Ignoring internal recirculation and mixing probe ebb.

accomplished a continuous flushing action on the drum wall. 6) It enhanced the air-liquid interrelation.

The flow of culture from the mixing probe (Figure 7, item 12) to the effluent probe (Figure 7, item 13) was relatively gradual and depended on the hydraulic loading. Because of this gradual flow, which in effect is an infinite compartmentalization, a more highly treated effluent could be produced than would have been possible with conventional systems. It should be emphasized that the liquid flow in a centrifugal field of 20 g (force in the algatron) acts more or less as it it were a laminar flow, in that there is a gradual movement of liquid and a minimum of short-circuiting. By providing a relatively intensive internal recirculation, a controlled mixing was made possible and renewal was a "single" unit of volume.

b. External Recirculation. As stated previously, a primary objective was to work with relatively heavy concentrations of biomass, and thus to obtain those advantages which accompany the use of thin-layer cultures. The influent unstable solids concentration remains more or less at a given level. In domestic sewage, the nutrient concentration and BOD generally are quite low (BOD, 200-250 mg/l), and would be somewhat higher (BOD, 400-800 mg/l) in waste waters under prolonged space conditions. Consequently, if a combination of such a dilute influent and a biomass of the density needed to meet the full capacity of the algatron were used, the hydraulic loading required to furnish an adequate supply of nutrient would be so great as to wash out the culture.

Ideally, the biomass concentration in the reactor should be maintained constant. Therefore a continuous recirculation of separated biomass should be applied. In the experiments described in this report, variation of biomass concentration in the reactor was kept within a narrow range by applying a "semi-batch" type of recirculation of biomass. However, only average biomass concentrations were recorded, and the extent of the viability of the bacterial phase as yet remains open to question. Preferably, a continuous biomass recirculation regulated by an optical density sensing device should be used.

5.3 Illumination

Light was provided by four circular 32-watt fluorescent lamps placed within the drum and five incandescent lamps (reflector flood, 150 and 300 watt) arranged around the outside of the drum (cf. Figure 8). Light intensities at various regions of the drum surface are also indicated in Figure 8. Since the drum rotated at 430 rpm, the stationary point light source supplied, to some extent, an instantaneous periodicity as the culture was rotated between zones of maximum and minimum light intensity.

Light intensity was designed to more closely approximate that to be encountered in space than was possible in previous experiments with the algatron. Even the higher intensities which prevailed in the experiments described in this report are lower than those of the light side of an orbiting space capsule (10,000 ft-c). This lower than attainable light intensity indicates that heavier concentrations of biomass could be profitably used in space.

In our experiments, it was assumed that the culture was light saturated when the intensity of the light that had passed through the culture at any given reference point was 200 ft-c.

5.4 Temperature

Owing to the intensity of the light source and the maintenance of a relatively constant ambient temperature, the temperature of the culture remained constant, namely 34°C. ± 1.9°C. The rotation of the drum, as well as the presence of a large liquid-air specific surface of about 1 sq cm/cc served to prevent the buildup of heat, which normally would have accompanied the application of an equivalent amount of light energy to a culture growing in a conventional growth unit, unless the latter was equipped with an elaborate cooling system.

The small fluctuations in temperature that did take place were the result of variations in room temperature (from 20°C to 28°C) and relative humidity (from 50% to 60%). The intensive evaporation taking place in the algatron had a tendency to cool the culture, and thus the observed fluctuations were less than those of the room temperature.

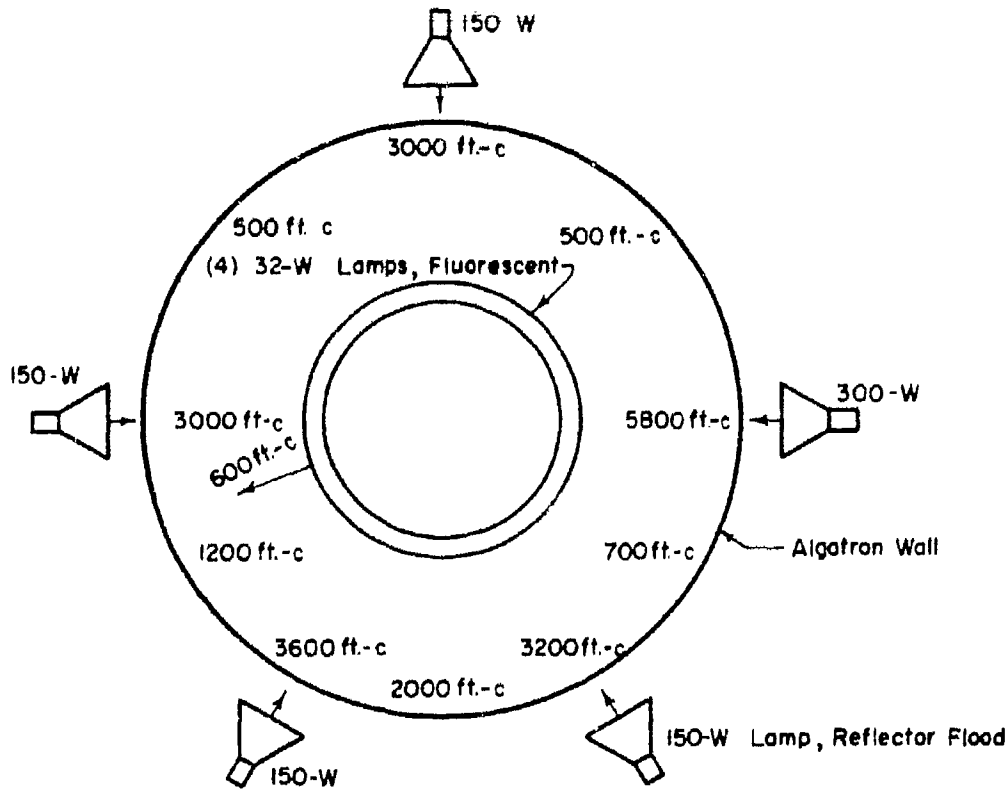

FIGURE 8. LIGHTING ARRANGEMENT FOR INTENSIVE WASTE REGENERATION IN THE 12 in. x 24 in. ALGATRON

5.5 Medium - Characteristics

Since an important objective of the research was to investigate waste treatment and nutrient removal under conditions which would be encountered in space, a heavily concentrated influent was used. The influent was constituted on the assumption that "liquid" wastes produced in a spacecraft would consist of the following: 1) human physiological wastes (feces and urine); and 2) wash water--bathing water, dishwater, laundry water, and other waters used in maintaining cleanliness in the cabin. For our purposes, the water consumption per astronaut was estimated as being 37.85 l/day on short flights and 18.9 l/day on long flights (six weeks or longer). Therefore, influent used in the experiments had the following components: 1) human urine proportional to a "standard" man (cf. Table III for a list of specifications of a "standard" man); 2 feces proportional to a "standard" man; and 3) primary domestic sewage. Primary sewage was used to represent the diversity of wash waters listed above. Since domestic primary sewage contains an appreciable amount of human physiological wastes, in the experiments it was diluted with water on a 1:1 basis. It should be noted that the diluted sewage undoubtedly had a much higher BOD and greater supply of algal nutrients than that of ordinary wash water (i.e. water that has been used for personal cleanliness). The composition of the primary sewage used in preparing the influent feed is given in Table IV.

TABLE III

WASTE PRODUCTION BY A "STANDARD" MAN[a]

Age		30 yr
Weight		164 lb (74.5 kg)
Height		5 ft 10 in. (1.8 m)
Diet		Normal
Physical Activity		Moderate
Urine Production (average)		1200 ml/day
Feces Production (average)	Wet Weight	180 gms/day
	Dry Solids	16.3%
	Volatile Solids[b]	88.0%
	Ash	12.0%
	Dry Solids Production	31.0 g/day

[a]In all experiments, human wastes came from the same individual. Except for height, the characteristics outlined in the table are his.

[b]Ashed at 600°C.

TABLE IV

COMPOSITION OF PRIMARY SEWAGE USED IN PREPARING INFLUENT FEED

Item	Average (mg/l)	Range (mg/l)		After Dilution 1:1 (avg.) (mg/l)
		Min.	Max.	
BOD	128	89	162[a]	64
Total Nitrogen	34	20	54	17
NH_4-N[b]	44	26	69	22
Organic N[b]	10	0	21	5
Phosphorous	21	10	50	10.5
Magnesium	24	17	38	12
Calcium	26	20	34	13
Total Solids	370	290	440	185
Volatile Solids	168	124	202	84
Suspended Solids (Total)	92	70	117	46
Suspended Solids (Volatile)	78	-	-	39
Dissolved Solids (Total)	278	-	-	139
pH	7.4	7.0	8.0	7.6

[a]Standard deviation, 14 mg/l, i.e., data fairly close to the mean.

[b]See discussion in text.

5.6 Medium - Preparation and Sampling

In preparing the influent feed, fecal matter was blended with water for about three minutes at high speed in a Waring blender. The resulting suspension was passed through a 1.5-mm sieve to remove coarse fibrous material that may have been present. The washed fibrous material amounted to less than 1% of the total matter. All feed components were mixed together and stored in the feed reservoir (cf. Figure 7, item 2). Influent feed components used in each run are listed in Table V. Fresh feed was prepared each day. Feed contained in the influent reservoir was mixed once each hour for 10 minutes with an automatically activated stirrer (Figure 7, item 1). After the 10-minute mixing period, the

reservoir contents were programmed to stand undisturbed for 10 minutes so that the larger particles could settle out of suspension. A portion of the remaining suspension was then metered to the influent injection device by way of an electronic volumeter and a Sigma pump (Figure 7, item 5). The Sigma pump was adjusted so that the time required for transporting the feed from the volumeter to the culture vessel was approximately 20 minutes. The provision for settling the larger particles was a preventive measure to keep the feed line and other parts of the algatron system from becoming clogged.

Influent feed as described in Table VI is the average composition of the feed as it was injected into the culture. The concentration of some of the components of the feed at this point was somewhat less than that of the same components in the original mixture, since some were removed in the form of settled material. Nevertheless, since the feed reservoir effluent port was placed approximately 3 cm from the bottom of the vessel, most of the smaller settleable particles were carried with the influent stream into the culture.

Inasmuch as each day's supply of feed was kept in a nonrefrigerated reservoir, some decomposition must have taken place in the reservoir, and therefore outside the reactor. Samples of the feed were taken at the start and at the end of each 24-hour period and were analyzed for the appropriate constituents. Decrease in the BOD of the stored feed as a result of decomposition in the reservoir was surprisingly low, averaging only about ± 5% of the original BOD. The small decline undoubtedly was due to the state of relative anaerobiosis that invariably prevailed in the reservoir under the storage conditions. These conditions were the high initial BOD and the anaerobic state of the components. Possibly the fact that the nonacclimated aerobic bacteria were in the lag phase of their growth also contributed to the relatively high degree of stability of the BOD during the first 24 hours.

Despite the diversity of the feed components, fluctuations from the mean values listed in Table VI were small. The coefficient of variation of the 5-day BOD was only about 5%, depite the intrinsic fluctuations in the BOD test itself. The coefficient of variation of nitrogen concentration was approximately 6%; and that of phosphorous, 7%.

The relative composition of the feed as regards the ratio of organic to ammonia-nitrogen varied significantly during a 24-hour storage period in the reservoir. At the start of a 24-hour period, most of the nitrogen was in an organic form--probably as urea. The ammonification of the organic nitrogen was quite rapid, and at the end of a 24-hour period more than 75% of the nitrogen was converted to the NH_4^+ form, whereas in the fresh feed, at least 50% of the nitrogen was in the organic form.

As judged from the tentative composition of the influent feed, the latter in turn being based on the characteristics of our so-called standard man, the organic and nutritive composition of the wastes discharged by such a man is approximately that described in Table VII.

The average values listed in Table VII are lower than those usually reported in the literature with respect to domestic sewage production per capita for an average community in the United States. For example, a daily output of 50 to 60 g BOD/capita generally is used as a basis in designing a treatment plant for an average community. However, this value represents all sources of domestic sewage, including such items as toilet tissue, ground garbage, and waste waters from commercial units, small industries, supermarkets, etc. The added BOD due to these components need not be considered in making estimates of the BOD of an astronaut's daily output of wastes, since obviously all such wastes will be kept at a minimum in a space vehicle or station.

A reasonable estimate of the BOD of the daily wastes produced by an astronaut would be from 1/3 to 2/5 of the per capita wastes of an average community. However, to arrive at a more firm estimate, more information is required with regard to expected organic and nutrient composition of the astronaut's wastes. The ultimate BOD of the feed used in this study may have been as much as 2 to 3 times that of the 5-day BOD (the type listed in the tables), especially in view of the heavy concentration of ammonia.

Although most of the suspended solids of the feed were converted into animate matter in the reactor (according to microscope examinations), the amount of BOD and algal nutrients in the supernatant of the centrifuged feed was nevertheless measured. Observations indicated that the suspended

TABLE V

INFLUENT FEED COMPONENTS

Run	Primary Sewage Diluted 1:1 (liters/day)	Total Liquid (liters/day)	A.P.[a]	Urine (ml/day)	A.P.[a]	Feces Wet Wt. (g/day)	A.P.[a]
1	13.8	14.1	0.75	210	0.175	21	0.194
2	13.8	14.1	0.75	210	0.175	40	0.222
3	13.8	14.1	0.75	270	0.222	40	0.222
4	13.5	14.1	0.75	540	0.444	80	0.444
5	13.2	14.1	0.75	810	0.666	120	0.666

[a]A.P. - Astronaut proportions - based on overall water consumption of 5 gallons (18.9 liters)/astronaut/day and "standard" man (cf. Table III) wastes characteristics (180 g feces/day, 1200 ml urine/day).

TABLE VI

INFLUENT FEED COMPOSITION[a]

Run	A.P.[b] Organic	BOD 5-day (mg/l)	Total[c] Nitrogen (mg/l)	$PO_4^{\equiv}$[d] (mg/l)	Mg^{++} (mg/l)	Ca^{++} (mg/l)	Total Solids		Susp. Solids	
							(mg/l)	(% Volat.)	(mg/l)	(% Volat.)
1	Approx. 0.185	242	146	50	13	17	844	49	176	79
2	Approx. 0.2	268	154	60	14	18	926	49	212	79
3	0.222	288	170	66	14	18	940	49	215	79
4	0.444	530	310	110	17	24	1526	51	364	81
5	0.666	810	450	146	21	32	2230	54	506	82

[a]At 10S Sampling point -- Figure 7.

[b]See footnote to Table V.

[c]Contains organic nitrogen and NH_4^+ nitrogen with varying relative degree of concentration (see text).

[d]Over 90% orthophosphate; polyphosphate varies from 0-10%.

TABLE VII

CHARACTERISTICS OF THE WASTES DISCHARGED BY A "STANDARD" ASTRONAUT

Run[a]	BOD[b] 5-day (g/day)	Total[b] Nitrogen (g/day)	$PO_4^{\equiv}$[b] (g/day)	Mg^{++} (g/day)	Ca^{++}[b] (g/day)	Solids[b]	
						Total (g/day)	Suspended (g/day)
3	14.2	12.4	4.2	0.98	1.16	59.6	15.2
4	14.7	11.4	4.5	0.54	0.72	50.5	11.8
5	14.1	11.3	4.1	0.44	0.67	44.9	10.2
Avg.	14.4	11.9	4.3	0.65	0.85	52.2	11.9

[a]The uniformity of the amount of primary sewage added to the feces combined with an increase in amount of physiological human wastes, as well as experimental conditions, all contributed to the decrease in values as the study progressed from one run to the next.

[b]All values based on dry weight.

solids constituted about 22% of the total solids in the feed. They also showed that 80% to 95% of the filterable suspended solids (Millipore bacteriological filter) were removed from suspension by centrifugation at 750 x g for 15 minutes. The proportion of the total suspended solids removed by centrifugation depended on the state of the internal coagulation of bacterial and macromolecules, amount of finely divided suspended solids, age of the feed, insolubility of organic compounds, etc. The high-speed blending of fecal material, removing coarse fibrous material through screening, intermittent mixing, and settling of the larger suspended solids in the feed supernatant all combined to cause a relatively high percentage of BOD and nutrients to remain in the supernatant. The extent of these effects are indicated by the data in Table VIII.

TABLE VIII

PROPORTIONAL COMPOSITION OF FEED SUPERNATANT

Composition	Supernatant (%)			Settleable Solids (Centrifuged) (%)		
	Avg.	Min.	Max.	Avg.	Min.	Max.
BOD	89	82	94	11	6	18
Nitrogen	95	91	98	5	2	9
$PO_4^{\equiv}$	88	84	91	12	9	16
Ca^{++}	91	83	95	9	5	17
Mg^{++}	87	75	94	12	9	16

In recent years many of the researchers engaged in work on the kinetics of biological systems have resorted to the use of soluble media, preferably synthetic media (e.g. "artificial sewage"). The information presented in Table VIII indicates that by properly preparing (blending) natural wastes, at least 90% of the nutrient content and BOD either would be in a soluble form or in such a finely divided state as to remain suspended

despite exposure to centrifugation at 750 x g for 15 minutes. The BOD and the nutrient composition were fairly constant. By using "natural" media, the expected error resulting from the presence of settleable material probably was smaller than the error stemming from the use of artificial media. The latter at best is only an approximation of conditions as they are met in nature.

5.7 Biomass - Organisms and Source

The bacterial phase of the biomass consisted mostly of types found in natural sewage, since sewage was the suspending medium. No attempt was made to maintain a uni-algal culture. Instead, those types of algae were fostered which adapted or adjusted themselves to the unique conditions found in the algatron. A reservoir of strains and species of algae and bacteria as constituted by the algatron provided a safeguard against the loss of a particular strain or species, and at the same time ensured the dependability of the biological phase of the system. Occasionally, however, algae obtained from cultures maintained at a higher temperature were used to augment the number of algae in the reactor.

The composition of the initial cultures are outlined in Table IX. It should be noted that an all-bacteria culture was used in runs 3b and 4b. The bacteria used in these two runs were obtained from a pilot activated sludge sewage treatment plant. The two runs were conducted to provide information for comparing the treatment capacity of an activated sludge culture with that of a mixed culture of algae and bacteria, both being grown in an algatron.

Chlorella spp. generally constituted the predominant algal group. On occasion, when conditions were suitable, Oscillatoria spp. became the more abundant type. In the studies a comparison was made of the treatment capacity of one type of culture (Chlorella) with that of the other (Oscillatoria).

5.8 Biomass - Concentration

Reproducible results require that the density of the biomass be kept at a constant level. One method of maintaining a given degree of concentration is to regulate the hydraulic detention period to coincide

TABLE IX

RELATIVE COMPOSITION OF INITIAL ALGAL CULTURES

Run	Source of Culture	Temp. Range in Source (°C)	Proportion in Initial Culture (%)	Algal Species	Approximate Proportion in Source (%)
1	Stock Bath	35-38	100	Chlorella Oscillatoria Others	< 95 > 5 traces
2	Stock Bath	35-38	70	Chlorella Oscillatoria Others	< 95 > 5 traces
	Microterella	33-37	30	Chlorella Oscillatoria Others	50 (approx.) 50 (approx.) traces
3a	Stock Bath	35-38	70	Chlorella Oscillatoria Others	< 95 > 5 traces
	High-Rate Pond	20-33	30	Scenedesmus Chlorella Others	< 80 > 20 < 1
3b	Activated Sludge Unit	20-26	100	none	--
4a	Stock Bath	35-38	30	Chlorella Oscillatoria Others	< 95 > 5 traces
	High-Rate Pond	20-33	50	Scenedesmus Chlorella Others	< 80 > 20 > 1
	Growth Units	22-25	20	Chlorella Others	+ 99 traces
4b	Activated Sludge Unit	20-26	100	none	--
5	Stock Bath	35-38	60	Chlorella Oscillatoria Others	95 5 traces
	High-Rate Pond	20-33	40	Scenedesmus Chlorella Others	80 20 > 1

with the biological detention period. The latter is determined by the rate of growth of the organisms involved. However, since the hydraulic loading has a given level in most cases in practice, varying it to provide "steady state" conditions with respect to concentration would have been undesirable. Moreover, if the organic and nutritive loadings constitute a variable under investigation, varying the hydraulic loading would involve corresponding deviations in the concentration of the medium--again a departure from conditions in practice. It should be emphasized that, particularly in a closed system, both the volume of the liquid wastes and the concentration of the wastes are predetermined with a high degree of accuracy. Thus, the hydraulic and the organic loadings are apparently established at a given level, which is determined by amount of water consumption and waste discharge rates, and which cannot be altered to maintain a steady state with regard to culture concentration.

A method of maintaining a biomass at a constant concentration without interfering with the hydraulic and organic loadings is to recirculate a part of the separated biomass slurry. By means of such a recirculation and because of the relative retention of the algal cells in the algatron, it is possible to buildup a relatively heavy concentration of algal cells, even with a very short hydraulic detention period.

The biomass was maintained at an average of 2060 mg/liter. At this concentration, the light intensity was sufficiently great as to ensure light saturation in the culture. The culture was judged to be light saturated because with only one surface of the culture illuminated, the light intensity at the nonilluminated surface was 200 ft-c.

The influent was introduced into the reactor at the rate of 14.1 l/day. This loading rate was equivalent to a 0.36-day detention period, since the reactor volume was 5 liters. Under conditions other than those encountered in the algatron system, such a short detention period would have necessitated a high return recirculation rate, since the biological detention period ranged from 0.7 to 1.5 days. However, since the evaporation rate averaged 8.0 liters/day, the apparent detention period (reactor volume/effluent discharge) was 5.0/6.1 or 0.82 day. Whenever the biological detention period exceeded 0.82 day, the excess was centrifuged and the centrifuged biomass was returned to the reactor twice daily so as

to maintain the biomass at approximately 2060 mg/l. When the biological detention period was less than 0.82 day, biomass was withdrawn from the reactor twice daily.

Some variation in biomass concentration occurred within each 24-hr period because recirculation of the biomass had to be accomplished on a "semibatch" basis, i.e., centrifuging and returning twice each day. This variation was ± 220 mg/l.

5.9 Results

a. BOD and Nutrient Reduction. The extent of the reduction in BOD and nutrient concentration is indicated by the summarized data listed in Table X.

Reduction in BOD in excess of 95% was obtained in almost all of the experimental runs. BOD reduction as great as 2.16 g (5-day BOD)/liter of reactor volume/day was obtained in one run (run 5). Such a reduction is the equivalent of a 23.4 g reduction per sq meter of reactor surface per day. Minimum reduction was 1.05 g BOD/g of reactor suspended solids/day.

Extent of BOD reduction was about the same regardless of whether a bacterial biomass or an algal-bacterial biomass was used. This similarity indicates that perhaps at the organic loadings applied (maximum 0.444 A.P., cf. Table V) the rate of oxygenation was fairly adequate regardless of whether or not oxygen came from the ambient atmosphere or as a result of algal photosynthetic activity.

b. Nitrogen Removal. Nitrogen removals as high as 80% were obtained in the experiments in which algal-bacterial cultures were used. In those in which bacteria alone were used, most of the nitrogen was converted to nitrate. Maximum removal of nitrogen was 1.08 g/l reactor volume/day, or 11.7 g/sq meter/day.

Despite the extensive removal of nitrogen, the nitrogen concentration of the effluent exceeded that which would be permissible in those cases where there is to be a final effluent. The reason for this condition was the heavy nitrogen content of the influent feed.

c. Phosphorous, Calcium, and Magnesium Removal. Phosphate removal averaged about 60% in all experiments in which algal-bacterial cultures were used, and only about 34% in those in which bacteria alone were used. Variations in phosphate removal probably were the result of varying degrees of precipitation.

TABLE [illegible]

[illegible] AND NUTRIENT REDUCTION

[illegible]	[illegible]	[illegible]	[illegible]				[illegible] (mg/l)				$PO_4^{\equiv}$ (mg/l)				Mg^{++} (mg/l)				Ca^{++} (mg/l)				BOD Loading mg per liter of Reactor Vol.
			[illegible]	[illegible]	Conc.[a] Eff.	Red. (%)[b]	Inf.	Eff.[b]	Conc.[a] Eff.	Red. (%)[b]	Inf.	Eff.[b]	Conc.[a] Eff.	Red. (%)[b]	Inf.	Eff.[b]	Conc.[a] Eff.	Red. (%)[b]	Inf.	Eff.[b]	Conc.[a] Eff.	Red. (%)[b]	
[illegible]	[illegible]	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	55?	73.5?	5?	22	51	42.?	13	10	23	23	17	11	25	35.5	682
[illegible]	[illegible]	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	75.1?	[illegible]	31	71	45.?	14?	10	23	29.5	18	13	30	27.?	755
[illegible]	[illegible]	[illegible]			[illegible]	[illegible]	100?	1?	43?	95.3?	[illegible]	22	51	66.8?	1?	9	21	35.?	13	12	28	33.2	812
[illegible]	[illegible]	A.G.B.C.? *Chlorella?*	-		[illegible]	[illegible]	1?0	15	30	92.3	66?	19	43	71.1	14	7	16	50	13	8	18	55.4	812
[illegible]	[illegible]	A.C.[c]		[illegible]	[illegible]	[illegible]	[illegible]	--[f]	--	--	?6	43	100	34.?	14	12	28	14	13	13	30	27.6	812
[illegible]	[illegible]	A.B.C.B.? *Chlorella* and *Scenedesmus*	[illegible]	[illegible]	[illegible]	[illegible]	320	27	?2	90.7	110	28	65	74.6	17	11	25	34.2	24	12	28	50.0	1490
[illegible]	[illegible]	A.C.[c]	[illegible]	[illegible]	[illegible]	[illegible]	410?	--[f]	--	--	110	[illegible]	138	33.7	17	13	30	23.5	24	19	43	20.5	1490
		A.B.C.B.? *Chlorella* and *Scenedesmus*	[illegible]	[illegible]	[illegible]	[illegible]	450?	[illegible]	152	85.4	146	30	69	79.7	21	12	28	45?	32	14	33	55.2	2280

[a] [illegible] effluent after evaporation.

[b] [illegible] water for comparison with influent. Factor: 6.1/14.1.

[illegible]

[illegible]

[illegible]

[illegible]

From 25% to 50% of the calcium and magnesium were removed. As with phosphate, the variations in extent of removal probably were a function of different degrees of precipitation.

d. Relative Capacities of Chlorella and Oscillatoria in Treatment. According to the data listed in Table X, the extent of reduction in BOD, nitrogen, phosphate, calcium, and magnesium was slightly greater in the run in which Oscillatoria constituted the predominant algal type than in those in which other algal types were the more numerous. No detectable difference with respect to treatment was observed between Chlorella and Scenedesmus. However, in experiments in which Scenedesmus was introduced as the predominant algal type, Chlorella nevertheless soon superseded it in numbers if not in biomass.

e. Biomass Growth Rates. Biomass was related to total suspended solids assumed to be almost entirely animate in composition. Inasmuch as the concentration of biomass in the reactor was held fairly constant, it is possible to compare transfer yield values with those for specific growth rates. These values are summarized in Table XI and plotted in Figure 9. The relation between organic and nutrient loading to yield was linear. This indicated that at its relatively heavy initial concentration of biomass, the system was not loaded to its full capacity. The specific growth rate of the activated sludge biomass (cf. runs 3b and 4b, Table XI) was lower than that of the symbiotic biomass.

f. Water Regeneration. Water evaporation rates were measured daily. During a 3-month period of observation, the rate was 1.6 liters /liter of culture volume, or 17.3 liters/sq meter of culture surface. It averaged from 1.4 to 1.8 liters/liter day. The coefficient of variation was less than 6%. The high rate of regeneration obtained in the experiments, namely 17 liters/sq meter, indicates that this function could be easily carried on in an integrated system.

g. Oxygen Regeneration and CO_2 Absorption. Although the exact estimate of the algal growth within the biomass in the algatron cannot be made with the information at hand, it is possible to arrive at some concept of the amount of oxygen produced in the system. Making the extremely conservative assumption that only 50% of the symbiotic biomass was algal in nature, the algal yield in run 5--the highest attained in

TABLE XI

YIELDS AND BIOMASS GROWTH RATES

Run	Dominant Culture	Yield of Culture (mg/l)	Specific[a] Growth Rate (day^{-1})	Biological[b,c,d] Detention Period (days)	BOD Loading mg per liter of Reactor Volume
1	A.B.S.B.[e] Chlorella	900	0.436	2.29	682
2	A.B.S.B. Scenedesmus	979	0.475	2.10	755
3a	A.B.S.B. Chlorella and Scenedesmus	1048	0.526	1.90	812
3aa	A.B.S.B. Oscillatoria	1096	0.532	1.88	812
3b	Activated Sludge Bacteria[f]	466	0.226	4.42	812
4a	A.B.S.B. Chlorella and Scenedesmus	1810	0.879	1.04	1490
4b	Activated Sludge Bacteria	825	0.400	2.50	1490
5	A.B.S.B. Chlorella and Scenedesmus	2745	1.330	0.75	2280

[a] Concentration of biomass in the reactor averaged 2060 mg/l suspended solids.

[b] Hydraulic detention period based on influent--0.358 day.

[c] Hydraulic detention period based on effluent--0.82 day.

[d] Volume of reactor (culture)--5 liters.

[e] Algal-Bacterial Symbiotic Biomass followed by the predominant algal species.

[f] Activated sludge--mostly aerobic bacteria.

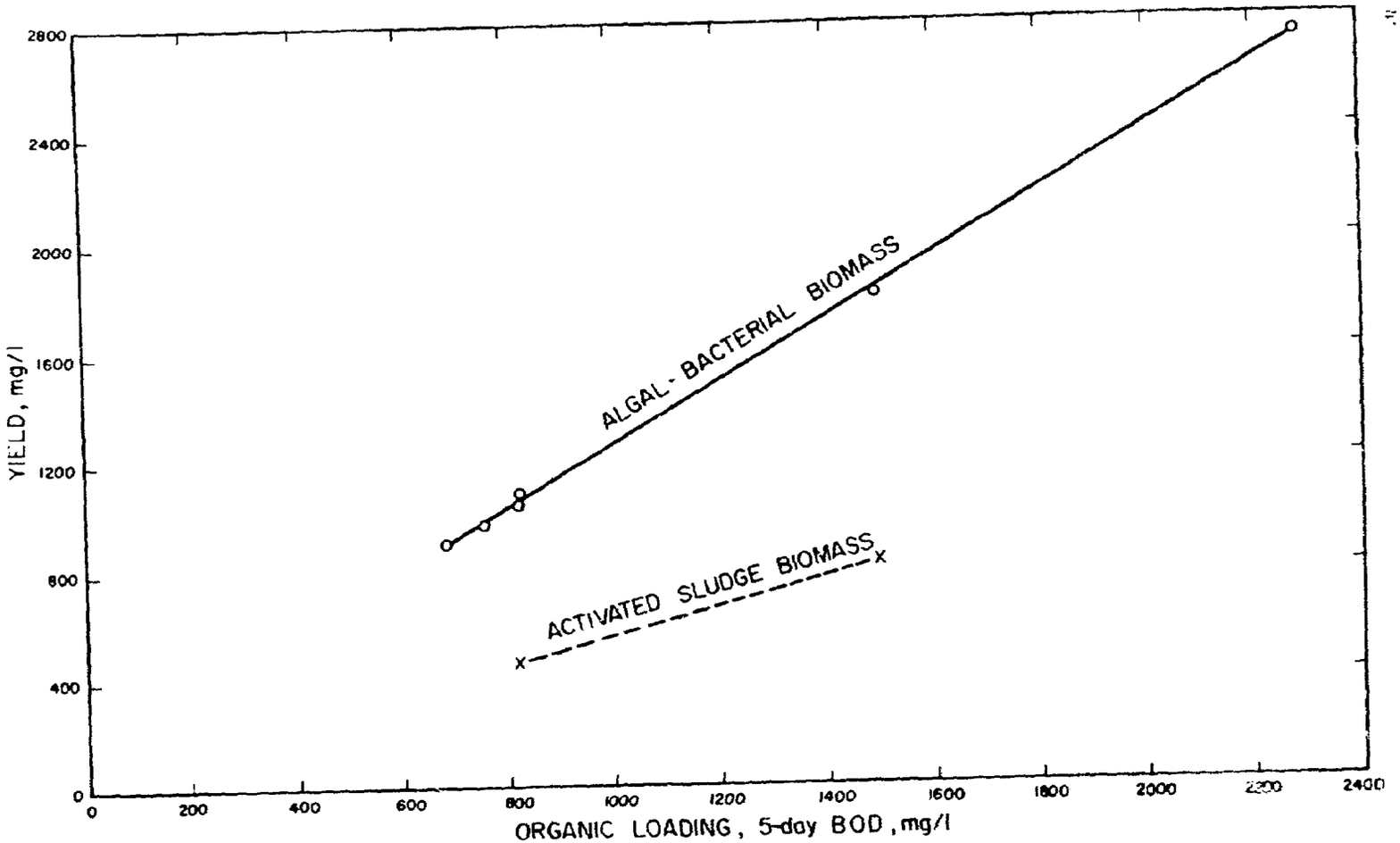

FIGURE 9 . BIOMASS YIELD AS A FUNCTION OF LOADING

the experiments--was 1370 mg/liter-day, or 14.8 g/sq meter-day. Assuming 1.6 g of oxygen produced per gram of algae grown, the oxygen production was on the order of 23.8 g/sq meter-day.

In considering these results, it should be noted that the culture was exposed to only an atmospheric concentration of CO_2, namely 0.03%. The only other source of CO_2 was that resulting from the decomposition of organic matter in the reactor. Higher yields and greater efficiencies would doubtlessly result in an atmosphere containing more CO_2.

6. REAERATION RATE

Since one of the advantageous features of an algatron is the high rate of gas exchange that can be attained with its use, a study was made of the rates of aeration that could be accomplished in the unit. An algatron with a horizontally oriented drum was used in the study. A photograph of the unit is shown in Figure 10. Except for feed and gas inlets and outlets, the unit was sealed at both ends. Other than the use of 24-hour settled sewage in one series of experiments, boiled distilled water was used as the liquid in most of the experiments. The sewage was used because its oxygen demand would increase the amount of oxygen required to reach saturation, and thus provide a wider range of oxygen uptake than was found to be possible with distilled water. Oxygen uptake rates were determined with the drum stationary and with it rotating, the former serving as a control. Liquid was passed through the system at rates equivalent to detention periods of 0.66 to 5.2 minutes. (The shortest possible detention period with the equipment was 0.66 minute.) Two volumes of liquid were used, namely 500 ml and 750 ml. The surface-to-volume ratio of the stationary liquid at the former volume was 0.36 and at the latter, 0.26.

The results obtained in the experiments are listed in Table XII. As the data indicate, with the distilled water volume at 500 ml (21% of the volume of the drum), rotating the drum brought about a dissolved oxygen concentration slightly in excess of saturation at all detention periods tried. The percent saturation ranged from 48 to 5[illegible] with the drum stationary. At a volume of 750 ml (31% of drum capacity), 100% saturation

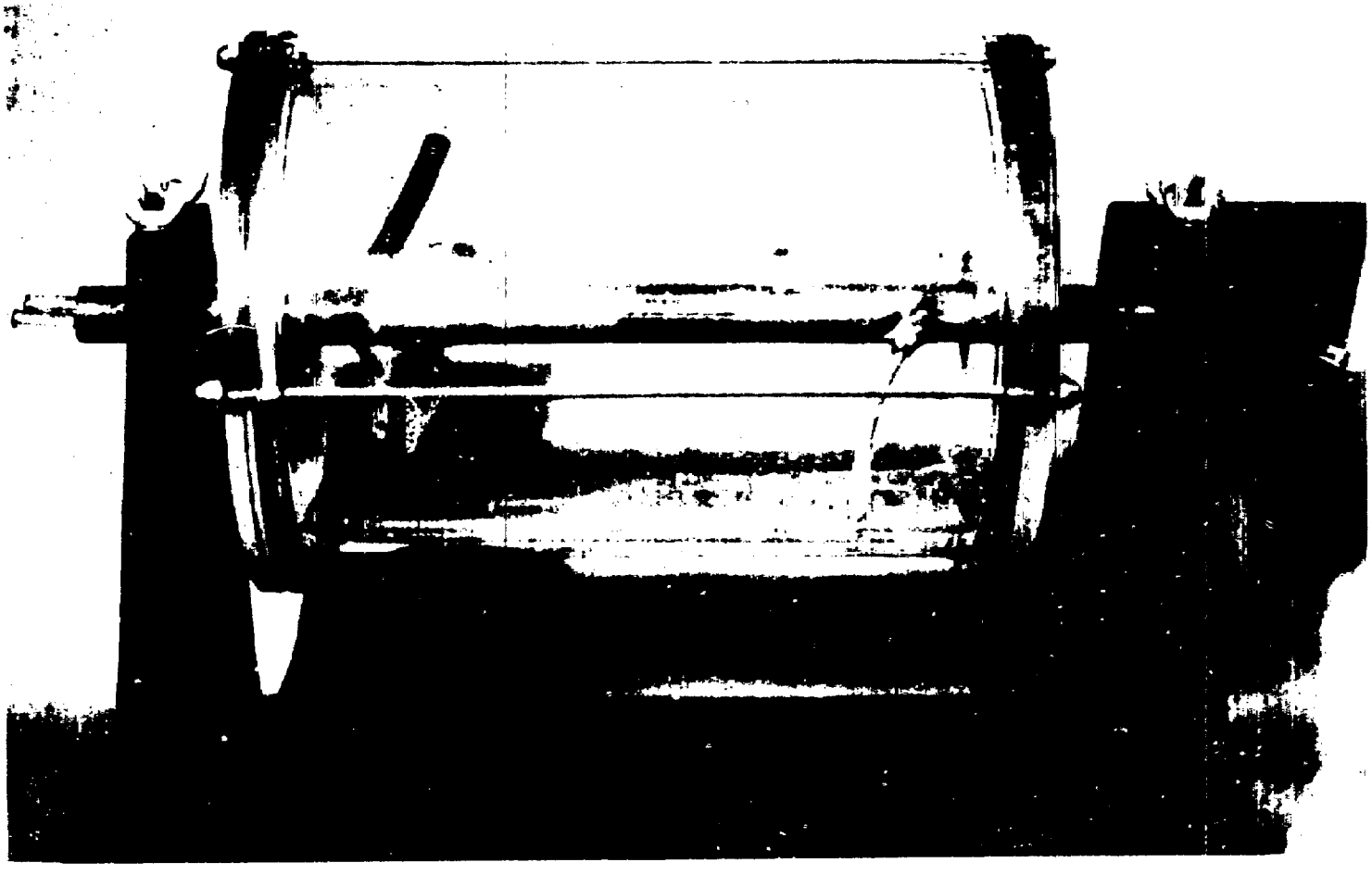

FIGURE 10. HORIZONTAL CONFIGURATION OF THE ALGATRON USED FOR REAERATION EXPERIMENTS

TABLE XII

RATE OF OXYGENATION IN THE HORIZONTAL ALGATRON

Run No.	Influent Liquid Dissolved Oxygen		Detention Period (min)	Volume of Liquid in Unit (ml)	Surface-to-Volume Ratio	Reactor Dissolved Oxygen			
						Stationary		Rotating	
	(mg/l)	(% saturation)				(mg/l)	(% sat.)	(mg/l)	(% sat.)
1	2.9	27	0.75	750	0.26	4.1	42	8.4	87
2	2.9	27	1.2	750	0.26	4.5	45	9.3	100
3	2.3	22	0.66	500	0.36	5.0	56	9.6	101
4	2.3	22	1.0	500	0.36	4.7	48	10.6	105
5	2.3	22	2.1	500	0.36	4.6	48	10.6	106
6	0.6	5	0.66	500	0.36	1.6	17	7.7	83
7	0.6	5	1.0	500	0.36	2.5	26	9.3	98
8	0.6	5	3.6	500	0.36	2.6	26	9.5	98

was reached at the 1.2-minute detention period when the drum was rotating, and 45% with it stationary. Lengthening the period to 5.2 minutes brought it to 49% when the drum was stationary, and 104% with the drum rotating. The rate of reaeration was considerably less when sewage was used and the drum was kept stationary, ranging from 17% to 26% at detention periods of 0.66 to 3.6 minutes; and from 83% to 98% with the drum rotating. The volume of the liquid was 500 ml in both cases.

7. DESIGN CONSIDERATIONS

7.1 Recirculation of Biomass in the Algatron System

a. General Considerations. The regeneration of heavy biomass concentration is a very important feature in the use of the algatron for life support systems within space vehicles. Using a concentrated active biomass would be advantageous to any biological reactor (usually applied in the fermentation industry and in biological waste treatment) in order to reduce the reactor volume requirements and costs of construction and maintenance. The requirement of reduced liquid volume, however, is critical in space life support systems.

The liquid discharge (reactor influent) is a fixed designed value which depends on the water consumption and waste discharge, values which are given according to the designed living conditions of the astronauts. Moreover, the organic and inorganic concentrations of the waste liquids depends on the given volume of total liquid discharge, since there is no absolute amount of organic and inorganic waste per astronaut.

From past experiments, it seems that oxygen generation is the major design factor; i.e., the oxygen requirement will determine the size of the biological reactors (volume and surface area), since the volume needed to meet the oxygen requirement of a space vehicle crew is greater than that needed for waste treatment, nutrient removal, and fresh water regeneration.

According to Beer's law, for a given light intensity, the concentration and the depth (volume) are inversely proportional. It was demonstrated that the maximum light conversion efficiency does not coincide with light saturation of the culture, nor with constant illumination.

Consequently, in a continuously mixed culture, the maximum light conversion efficiency, i.e., the maximum net yield, will lie at a concentration which is somewhere below that of light saturation conditions.

Figure 11 shows graphically the expected relation between the biomass concentration (X_1) and the specific growth rate (μ). The combined effect of available light for the photosynthetic biota and the general effect of density is expressed in the relation $\mu = f(X_1)$ for a given culture depth (reactor volume). Since the yield is a product of the specific growth rate and the concentration, the maximum yield can be computed:

$$\frac{dy}{dX_1} = \frac{d(X_1\mu)}{dX_1} = \frac{dX_1\ f(X_1)}{d\,X_1} = 0 \quad .$$

For a given algatron culture depth, a given light intensity, and a constant loading velocity L_v (mass-ratio of substrate to organism), and preferably for a constant substrate removal rate (M) per unit of organism mass, the concentration of biomass corresponding to the maximum yield can be found experimentally. In the last set of experiments a specific growth rate of 1.33 day^{-1} was observed when the biomass concentration was 2060 mg/l, and the net yield was 2745 mg/liter of culture per day.

It is assumed that with concentrations of 3200 to 3700 mg/l, the specific growth rate will remain above 1.0 day^{-1} for the same light intensity and reactor volume (constant culture depth). Thus the net yield is increased to a maximum level of about 3.5 grams biomass per liter per day. To keep the same organic loading velocity, the BOD loading should be increased from 2280 mg per liter of culture per day to approximately 4000 mg BOD per liter of culture per day. Since the BOD concentration in spacecraft waste waters are assumed to be constant at approximately 800 mg/l (cf. run 5, Table VI), the hydraulic loading to the reactor should be 5.0 liters of feed per liter of culture per day, as compared to the 2.81 liters/liter-day applied in run 5 (cf. Table VI). The hydraulic detention period (influent) would then be 0.2 day instead of 0.355 day.

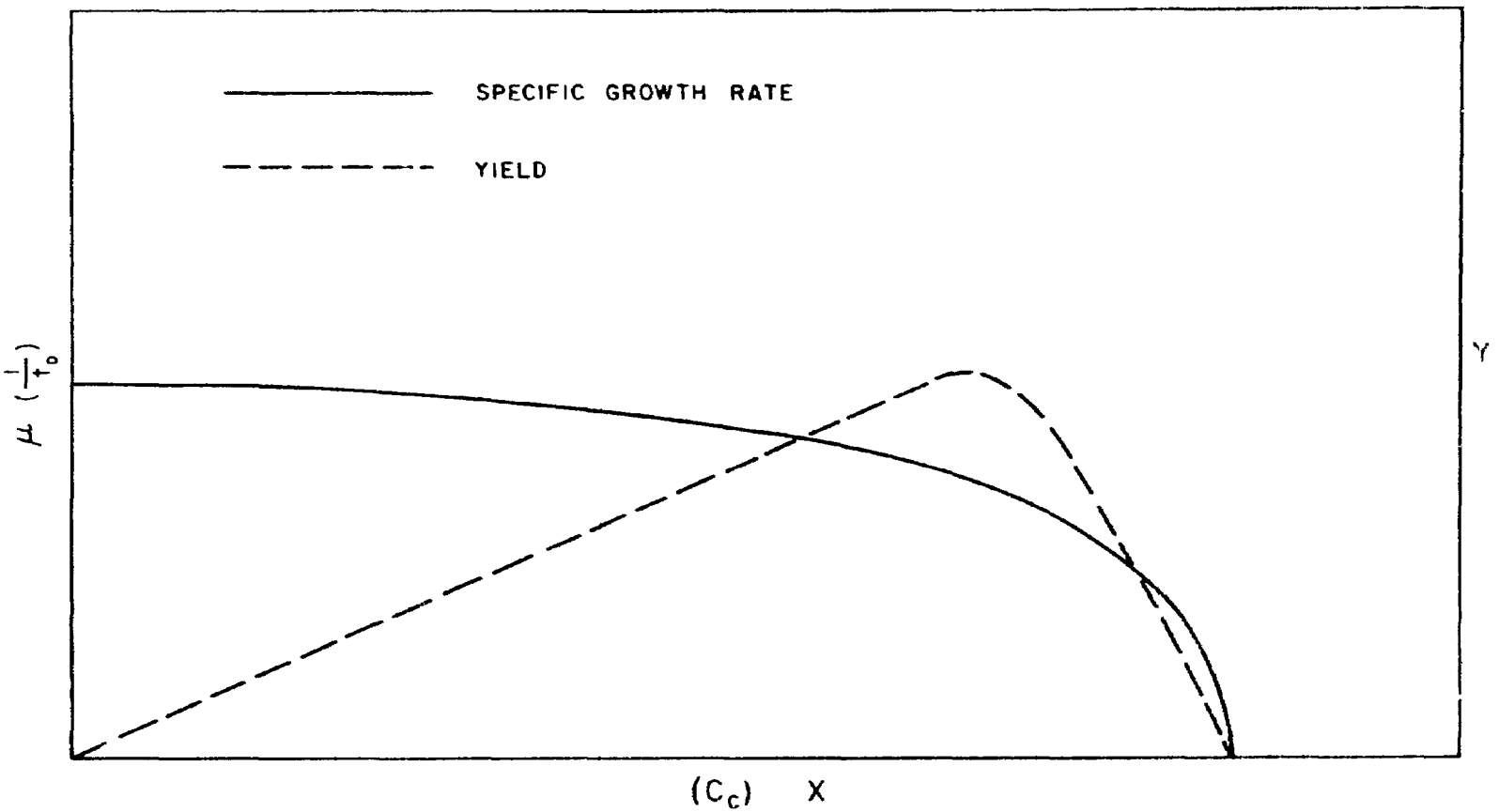

FIGURE II. EXPECTED RELATION BETWEEN BIOMASS CONCENTRATION (X), THE SPECIFIC GROWTH RATE (μ), NET YIELD (Y)

Since the evaporation rate in a given reactor is nearly constant and can be considered independently of the hydraulic loading, the detention period based on the effluent is decreased considerably, once the hydraulic loading is increased. Thus, using a detention period of 0.82 day, as based on the effluent characteristics in run 5 (cf. Table VI), the increased hydraulic loading would reduce the detention period to about 0.3 day or less.

The maximum attainable growth rate is about 2.0 day^{-1}; i.e., a biological detention period (organisms' "age") of 0.5 day. In practice and under optimal conditions, the specific growth rate will fall between 1 and 1.6 day^{-1} or a biological detention period of 1.0 to 0.625 day. Once the hydraulic detention period is shorter than the biological one, the concentration of organisms will decrease, since the culture eventually is "washed out." On the other hand, when the hydraulic detention period is longer than the biological period, the concentration of the biomass increases until some equilibrium is reached (usually at a concentration corresponding to a reduced yield).

If the hydraulic detention period cannot be adjusted to coincide with the biological specific growth rate (which is a relatively fixed value) to obtain maximum yield, two alternative methods can be used to overcome the "washing out" of the culture: 1) Adjust the retention of the biomass; 2) Separate the hydraulic and biomass phases and recirculate the biomass. Both methods are used in classical waste treatment--chiefly in trickling filter and in activated sludge systems. The algatron system can utilize each system, or a combination of the two.

b. Retention of Biomass. A highly concentrated biomass is retained on the filter medium (coarse gravel) due to the cohesive character of the gelatinous-like biomass. The liquid wastes are continuously flushed over the biomass, while the substrate is utilized by the organisms through diffusion. Thus, taking into account the liquid phase which has a momentary contact with the biomass, a high concentration of biomass is maintained despite a high hydraulic loading, and no flushing out of the culture takes place. The biological yield in such a system is extremely low. The effluent has a relatively high concentration of NO_3 and PO_4.

The retention of biomass despite a high hydraulic loading is easily attained in the algatron system, and retention is controllable to a high degree. The continuous centrifugal field prevailing in the algatron results in the accumulation of biomass at the outer part of the liquid phase and a much reduced concentration at the inner part. By using baffles and by varying the position of the effluent probe, it is relatively easy to maintain a high concentration of microorganisms with a rapid flowthrough rate of the liquid phase. This is illustrated by the sketch in Figure 12.

Making the algatron system solely dependent on biomass retention results in certain problems. 1) Mixing of substrate and biomass as well as exchange of gas would be hindered. 2) Uniform exposure of the biomass to light would not be attained. Thus, cells close to the drum wall would be overexposed, while those farther away would be underexposed. 3) Cells which were carried out with the liquid phase in the effluent would tend to be the smaller cells, and therefore the younger and more active cells. The larger cells, i.e., the older and less active ones, would tend to be retained. These problems could be minimized somewhat by the application of a more suitable mixing device and by use of internal recirculation systems. It appears preferable that the retention effect be used only as a part of the waste treatment method.

c. Separation and Recirculation. The reactor effluent is centrifuged so as to be divided into a relatively high concentrated slurry and a relatively clear liquid phase. The separation also can be accomplished by settling (as in activated sludge treatment). The former method is the one to be used in establishing an algal-bacterial symbiotic biomass, since it accomplishes treatment rapidly and with a lower volume requirement. Most likely the separation and recirculation of a part of the biomass slurry will necessitate the use of an additional mechanical unit. Inasmuch as the removal of nutrient as well as the reuse of water within a spacecraft involves the separation of biomass from the liquid phase, the use of a part of the slurry for recirculation seems to be the most logical approach.

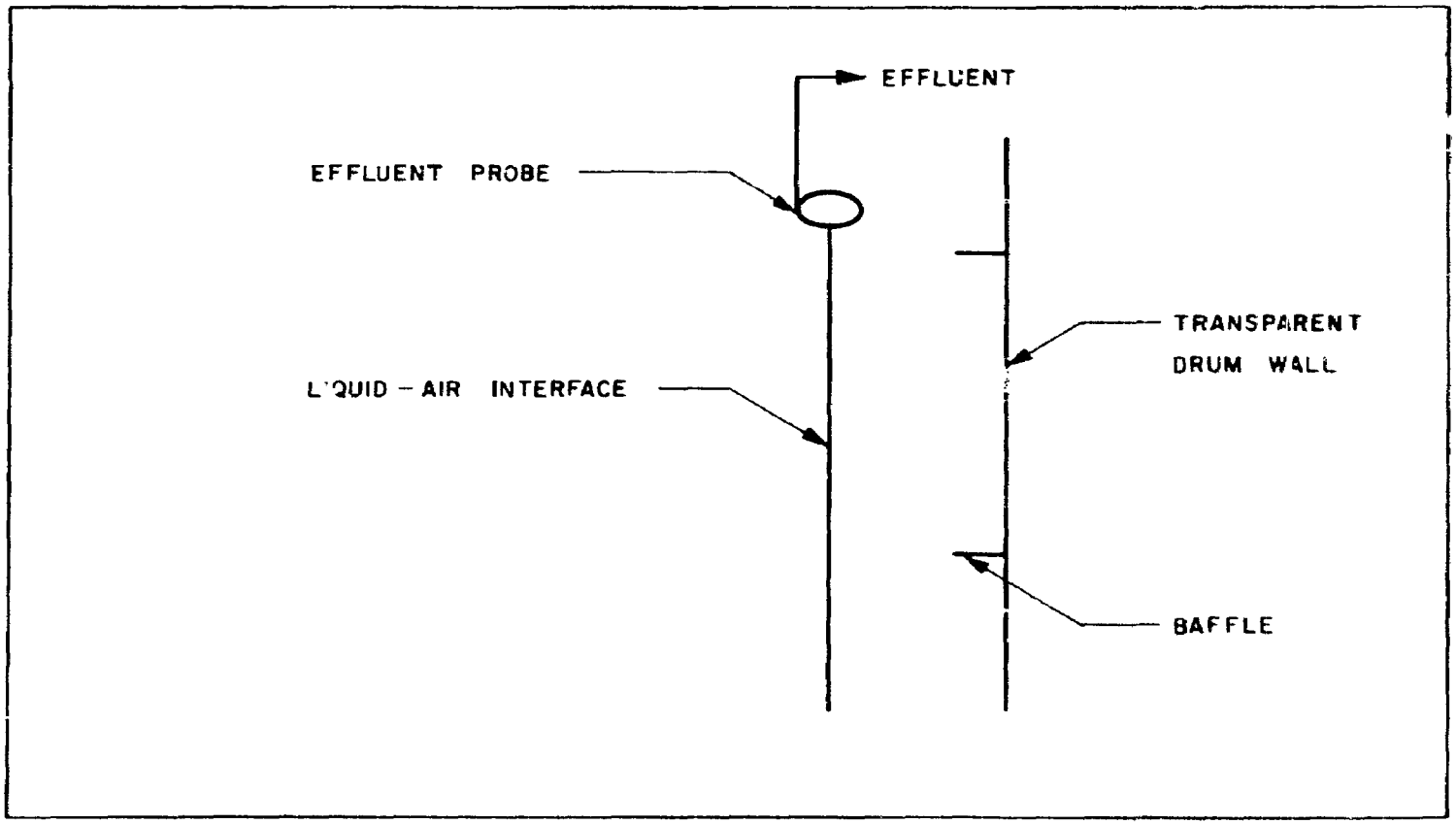

FIGURE 12. METHOD OF RETAINING HIGH CONCENTRATION OF BIOMASS AND A RAPID FLOWTHROUGH OF THE LIQUID PHASE

d. Recirculation System Design and Calculations. The design is illustrated in Figure 13. The following is a glossary of the symbols used in the figure:

γ_e = Recirculation ratio = R/F_e.

γ_i = Recirculation ratio = $R/J\ F_e = R/F_i = \gamma_e/J$.

E_v = Evaporation rate (1/day).

F_e = Flow rate based on effluent = $(F_i - E_v)$, (1/day).

F_i = Flow rate based on influent (1/day).

J = Flow rate ratio = F_i/F_e (due to evaporation in the reactor).

μ_n = Net specific growth rate of the biomass (day^{-1}).

R = Recirculation flow rate (1/day).

R_c = Concentration factor = X_1/X_r for cellular recycle.

R_r = Ratio due to reactor retention effect = X_1'/X_1 (R_r = 1 when no cells' retention occurs in the reactor).

θ_e = Hydraulic detention period (residence time) based on reactor effluent (days) = V/F_e.

θ_i = Hydraulic detention period based on influent = $V/F_i = V/J\ F_e = \theta_e/J$.

V = Reactor volume (liters).

X_o = Biomass concentration in the influent (mg/l).

X_1 = Biomass concentration in the reactor (mg/l).

X_1' = Biomass concentration leaving the reactor due to reactor retention ($X_1' = X_1$ when no cells' retention occurs in the reactor).

X_r = Biomass concentration in the recirculated fluid — after separation (mg/l).

Calculations: Since X_1, the biomass in the reactor, is constant (steady state condition plus optical density control), a cell continuity equation can be given:

$$V \frac{dX_1}{dt} = F_i X_o + R X_r + \mu_n X_1 V - (F_e + R) X_1 R_r = 0 \quad . \qquad (1)$$

It is assumed that $X_o = 0$; therefore,

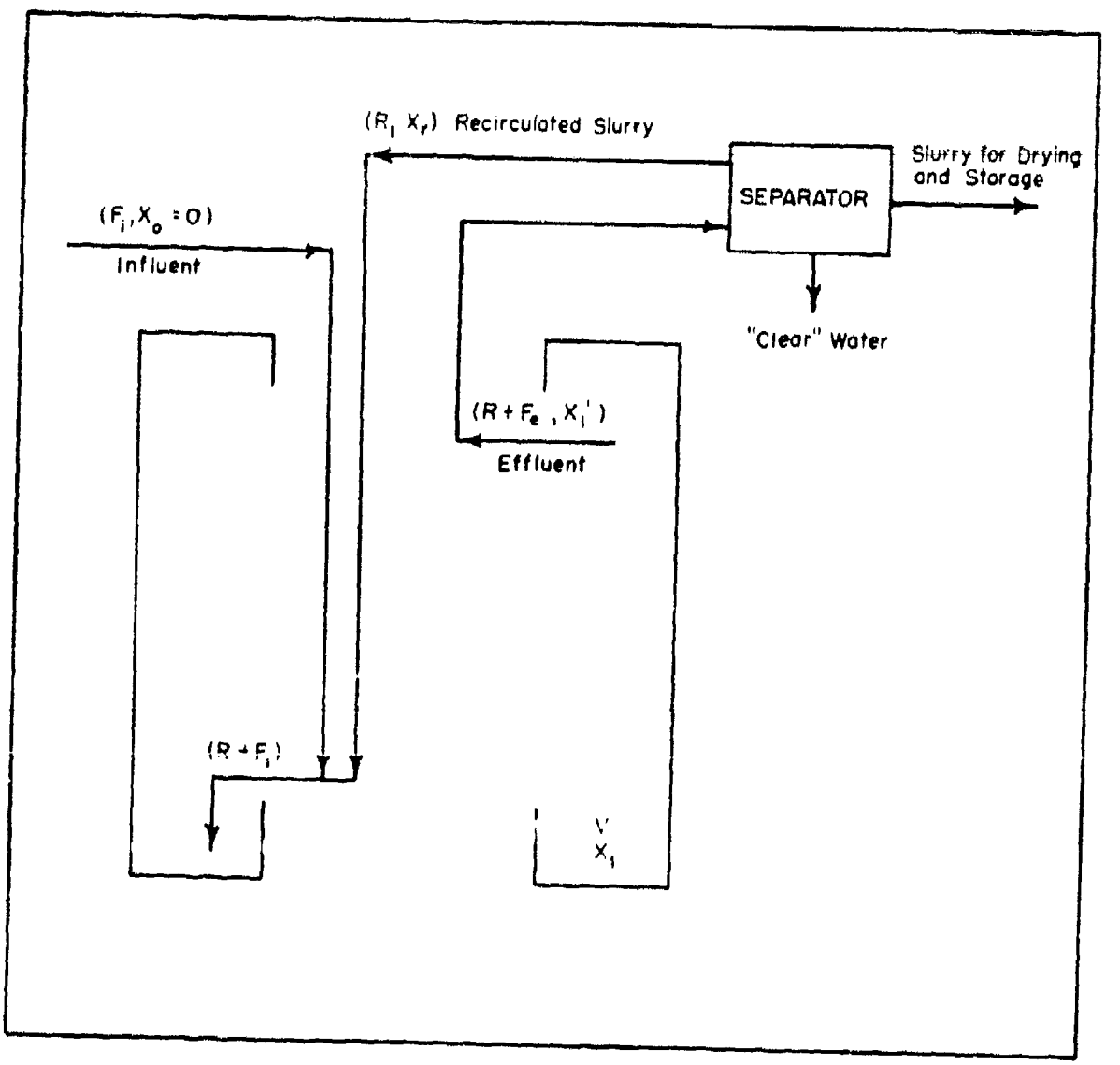

FIGURE 13. SCHEMATIC DIAGRAM OF ALGATRON RECIRCULATION

$$\frac{R}{V} X_r + \mu_n X_1 - \frac{F_e}{V} X_1 R_r - \frac{R}{V} X_1 R_r = 0 \quad , \quad \text{or}$$

$$\frac{R}{V} \frac{X_r}{X_1} + \mu_n - \frac{F_e}{V} R_r - \frac{R}{V} R_r = 0 \quad ,$$

by substituting

$$R_c = \frac{X_1}{X_r} \qquad \text{and} \qquad R = \gamma_e F_e$$

the following equation can be derived:

$$\mu_n = \frac{\gamma_e F_e R_r}{V} + \frac{F_e}{V} R_r - \frac{\gamma_e F_e}{V R_c}$$

since

$$\frac{F_e}{V} = \frac{1}{\theta_e}$$

$$\mu_n = \frac{1}{\theta_e} \left[\gamma_e R_r + R_r - \frac{\gamma_e}{R_c} \right] \qquad (2)$$

further transformation will give

$$\boxed{\gamma_e = \frac{\mu_n \theta_e - R_r}{R_r - \frac{1}{R_c}}} \qquad (3)$$

When $X_1 = X_1'$, $R_r = 1$, or

$$\boxed{\gamma_e = \frac{\mu_n \theta_e - 1}{1 - \frac{1}{R_c}}} \qquad (4)$$

Since $\gamma_i = \frac{\gamma_e}{J}$ Equations 3 and 4 can be written

$$\gamma_i = \frac{\mu_n \theta_c - R_r}{J\left(R_r - \frac{1}{R_c}\right)} = \frac{\mu_r J \theta_i - R_r}{J\left(R_r - \frac{1}{R_c}\right)} = \frac{\mu_n \theta_i - \frac{R_r}{J}}{R_r - \frac{1}{R_c}} \qquad (3A)$$

or similarly when $X_1 = X_1'$

$$\gamma_i = \frac{\mu_n \theta_i - \frac{1}{J}}{1 - \frac{1}{R_c}} \qquad (4A)$$

As an example, let us consider the situation of maximum yield per unit volume of reactor (i.e., V = 1 liter) with

X_1 = 3500 mg/l

θ_i = 0.2 day

θ_e = 0.3 day (based on evaporation rate E_v = 1.67 liter/liter-day)

X_r = 2% = 20,000 mg/l (concentration of slurry after separator)

μ_n = 1.0 day^{-1}

F_i = 5.0 liters/day

F_e = 3.33 liters/day

$J = \frac{5.0}{3.33} = 1.5$

$R_c = \frac{3,500}{20,000} = 0.175$

Assuming R_r = 1 (no retention in the reactor)

$$\gamma_e = \frac{1.0 \times 0.3 - 1}{1 - \frac{1}{0.175}} = \frac{-0.7}{-4.72} = 0.148$$

The recirculation flow rate R = $\gamma_e F_e$ = [illegible] x 3.33 = [illegible] liters/day.

Therefore, for one liter of reactor volume with influent flow rate

F_i = 5.0 l/day, the recirculation flow rate is approximately 0.5 l/day, i.e., 10% of the influent flow should be recirculated (γ_i = 0.099).

The effect of cell retention in the reactor on the recirculation rate can be illustrated as follows: If the retention is such that the concentration of cells in the effluent is equal to 70% of the concentration in the reactor,

$$R_r = 0.7$$

Then

$$\gamma_e = \frac{1.0 \times 0.3 - 0.7}{0.7 - \frac{1}{0.175}} = 0.08$$

and

$$\gamma_i = 0.053$$

Therefore, only 5.3% of the influent flow should be recycled as compared to 10% in the former case.

The effect of the concentration of the recirculated fluid X_r, on the recirculation ratio is quite significant. Assuming the same conditions as in the first example with only X_r being reduced to 15,000 mg/l instead of 20,000 mg/l, it can be shown that

$$R_c = 0.234$$

$$\gamma_e = 0.214 \quad \text{and}$$

$$\gamma_i = 0.142 \ .$$

Thus, a reduction of 25% in the concentration of the recirculated fluid results in an increase of more than 40% in the recirculation flow rate.

7.2 The Integrated Biological System

Using results obtained in run 5 (cf. Table X), it is possible to design an integrated biological system for the wastes of a "standard" astronaut. The design is summarized schematically in Figure 14. The design takes into consideration waste treatment, nutrient removal, and

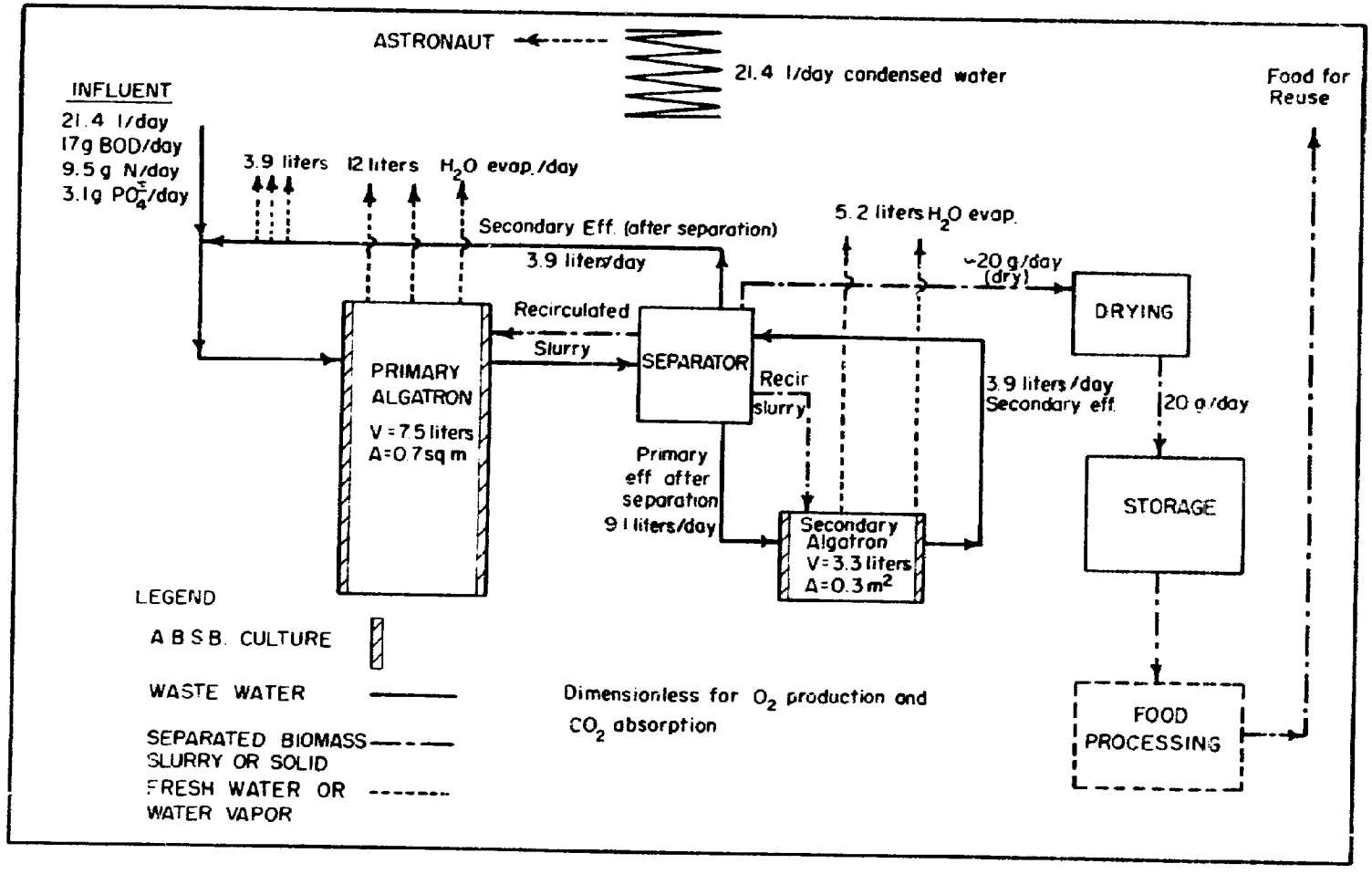

FIGURE 14. SCHEMATIC DIAGRAM FOR WASTE TREATMENT AND REGENERATION FOR ONE "STANDARD" ASTRONAUT

water production. It is not complete in that it does not include oxygen production and carbon dioxide absorption. According to the design, each day's wastes of a single astronaut would be converted to 21 liters of liquid wastes having 17 g BOD (5-day), 9.5 g nitrogen, and 3.1 g of phosphate. This liquid would be applied to a primary algatron having a culture volume of 7.5 liters or 0.7 sq meter wet (i.e., culture) surface area. Effluent from the primary drum, approximately 9.1 liters in volume (less in volume than the influent because of evaporation), would be applied to a secondary algatron. The drum area of the secondary algatron would be 0.3 sq meter. Thus the total drum area would be 1 sq meter, and the total culture volume, 10.8 liters.

Effluent from the secondary algatron, about 3.9 liters in volume, would be mixed with the wastes applied to the primary unit, or would be evaporated to produce water and dry solids. Thus, from 17-21 liters of low temperature distilled water would be produced each day by the system. The dry solids could be stored.

The concentration of biomass in each algatron would be maintained at 2000 mg/l, preferably by using a continuous recirculation of biomass operating in conjunction with an optical density sensing and control device. A bulk of about 20 grams of biomass would be removed from the system each day, dried, and then stored. In this way, carbon and other nutrients would be removed. The process, as well as storage of dried algae, should be nearly odorless.

If respiratory oxygen generation and CO_2 absorption are included, more algatrons are needed. A complete description of the physical system visualized for microbiological waste conversion and life support was set forth in the Second Technical Report of Project No. 8659, Task No. 86590, April 1965 [4].

Considerable modification of the system reported in 1965 is plausible in the light of added information collected during the current year. One possible major revision would be the reduction in volume of algal-bacterial cultures in direct proportion to algal yields (which are now 2.75 g/liter-day as compared with 1.5 g/liter-day in the earlier experiments). The indicated volume of culture required to support two astronauts is now $1.5/2.75 \times 550 = 300$ liters, and inasmuch as a 4.78-cm

length of an 18 in. diameter algatron is required per liter, the total length of algatron required is 1430 cm. At 122 cm length per 4-ft unit, the number of required units is 1430/122 = 11.8 or approximately 12. Thus, the projected number of 18 in. x 48 in. algatrons required to support two men has been reduced from 22 to 12. However, it should be pointed out that reductions in the number of algatrons below 10 may restrict water yield and the refrigeration capacity of the water reflux system; hence, it is unlikely that less than 10 algatrons would be employed in the system when two men are present regardless of the possibility that the theoretical regeneration volume could be further reduced.

Calculations indicate than an extended aeration activated sludge system for two men would have a volume of about 2 cu ft, a power requirement of 1/4 hp continuously, and weight of about 250 pounds. Due to savings in light, the energy of which would be absorbed by bacteria in an algal-bacterial system, the number of algatrons required to support two men could be reduced from 12 to 10 or less. Since each algatron weighs about 150 lb, a savings of 50 to 100 lb could be expected to result from separate treatment of wastes with extended aeration activated sludge. Use of a thermophilic activated sludge could further reduce the volumes and weights required without sacrificing evaporation capacity.

Technical difficulties with the microterella and the algatron have stemmed primarily from the miniature size of the systems rather than from the biological reactions of the systems. It thus has become clear that, to be most effective, further meaningful research with closed ecological systems must be done on a full scale with human subjects.

The improved effectiveness of research with human subjects will stem from the fact that internal operations and management can be carried out by the experimental subjects themselves, thereby improving reliability and vastly increasing the amount of valid information that can be obtained.

The studies already completed clearly indicate that through a combination of biological and physical systems, it should be possible to regenerate air and water indefinitely in a manned isolated system utilizing sunlight as the primary source of energy. Food, however, will be a limiting factor because algae can only be utilized to a limited extent as a food for

man, particularly when grown directly in his wastes. Thus, it is concluded that new (nonregenerative) food must be supplied to man in such a system. For voyages of lengths anticipated for the foreseeable future, about one pound of dehydrated food per day per man should be sufficient to meet his basic dietary needs. The nitrogen content of one man's food will be about 20 grams, whereas the nitrogen needed in the production of algae required to meet one man's daily oxygen requirement will be about 40 grams. Thus, the deficit in nitrogen between human diet and algae is about 20 grams per day. This deficit must be made up with supplementary nitrogen. At 20 grams per day the supplementary nitrogen requirement would be about 20 pounds per man per year. Similar calculations indicate that about two pounds of phosphorus and perhaps one pound of trace minerals would also be required to supplement human sewage as a nutrient for algae in order to maintain an efficient regnerative culture. Thus, about 400 pounds of dehydrated foods and mineral supplements will be required per man-year. As these substances are utilized, dehydrated algae will be produced in the system and stored in place of the food and supplements consumed.

Even numbers of algatrons are essential in any real space system and the units should be counterrotating for gyroscopic stability and control. Physical principles indicate that a fine degree of rotational control of the entire system could be attained by shifting mass within the counterrotating algatron units. In a weightless environment, it is possible that one-third of the rotating units could be placed with their axes at right angles to each other in the X, Y, and Z axes of a spacecraft. In this case a minimum of six algatrons (two on each axis) counterrotating could give complete internally controlled orientation of a craft without use of external jets and consequent loss of mass. Problems of illumination would, of course, be increased by having the algatrons oriented along three different axes.

Figure 15 shows schematically how a section of a large toroidal space station would look with the intensely illuminated algatron chamber separated from the gently illuminated living and control chamber. Figure 16 shows how the algatrons in such a space station would appear as viewed from the sun. Unevenly loaded counterrotating algatrons at the periphery would impart a slow spin to the system which in turn would impart

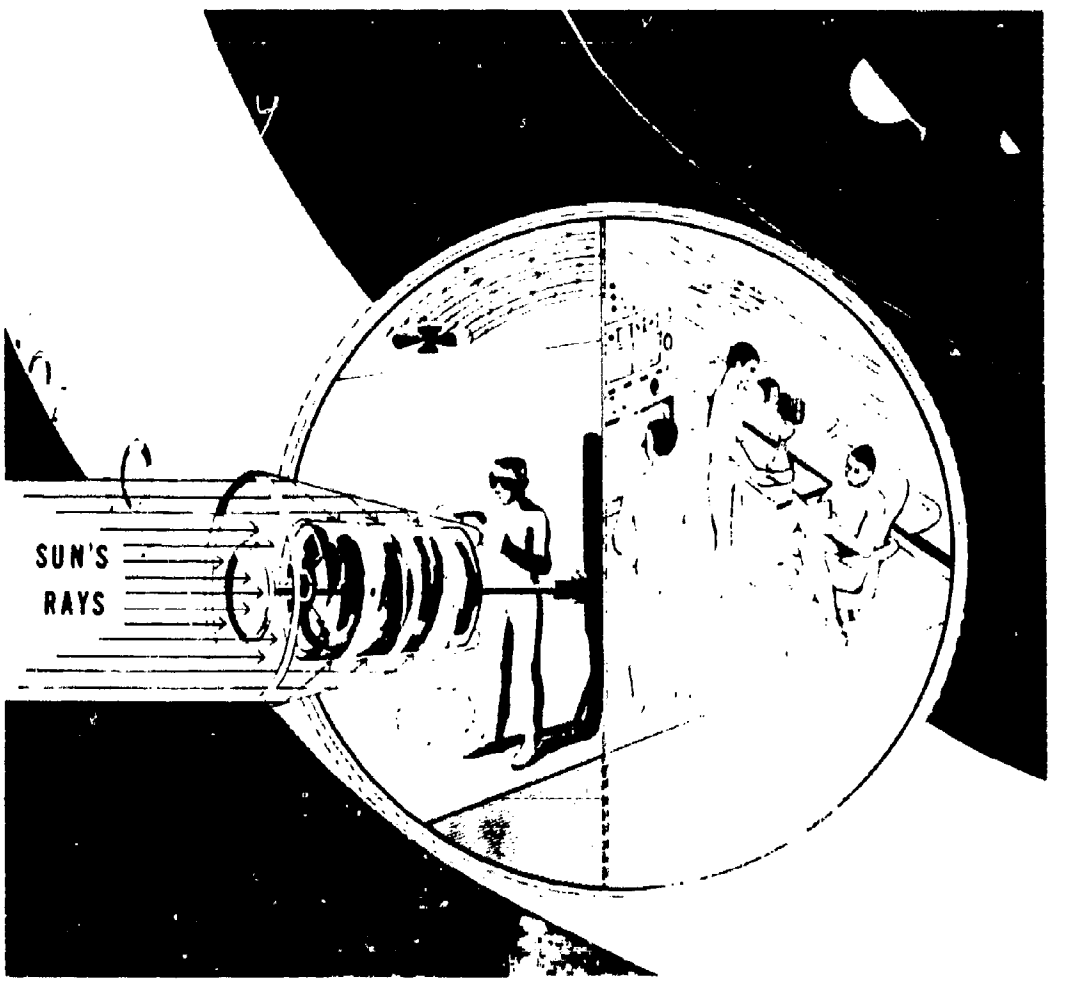

FIGURE 15. SCHEMATIC DESIGN OF TOROIDAL SPACE STATION SHOWING ALGATRON IN ILLUMINATION CHAMBER

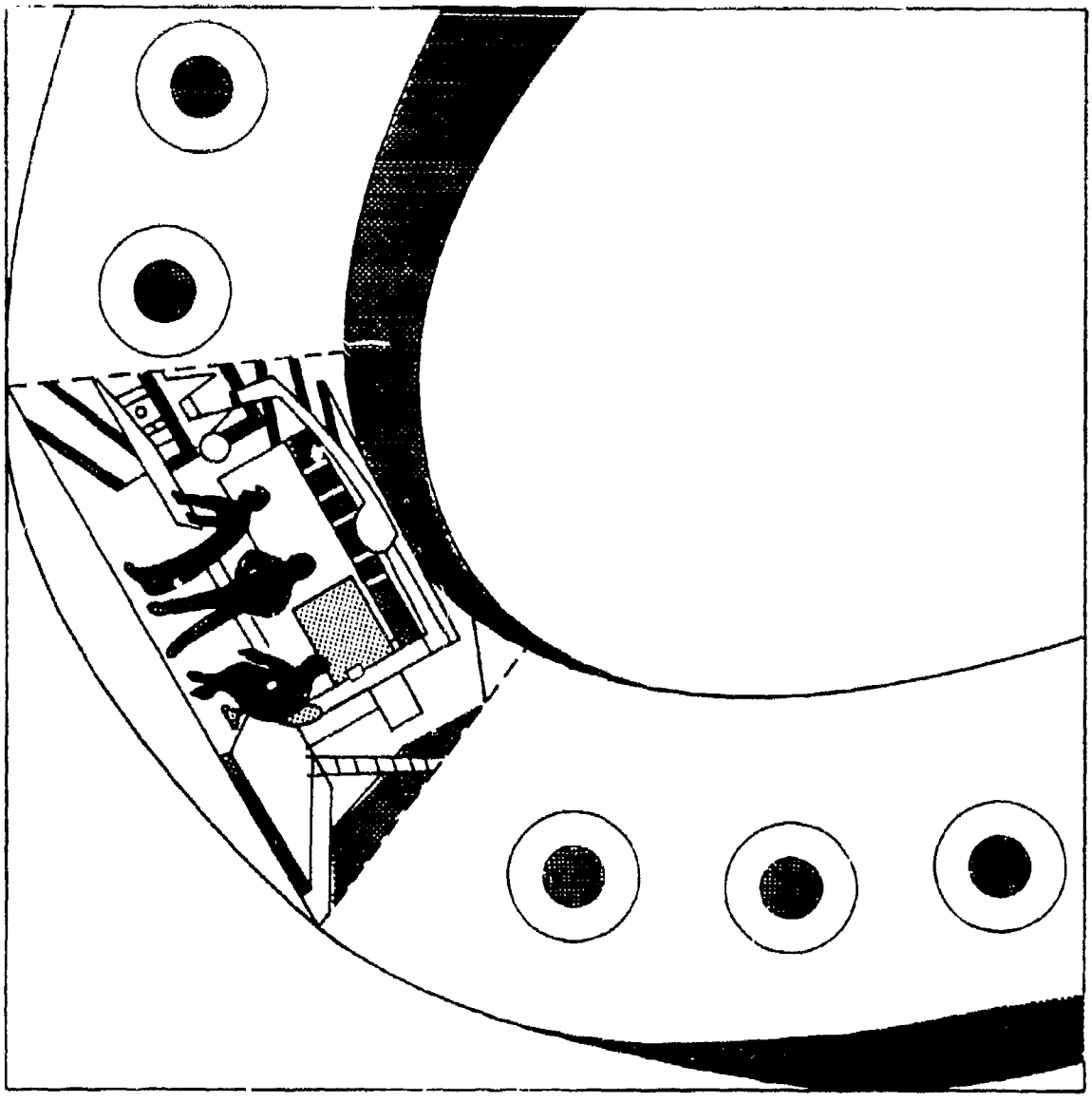

FIGURE 16. ARTIST'S CONCEPTION OF HYPOTHETICAL SPACE STATION WITH ALGATRONS VIEWED FROM THE SUN

a slight artificial gravity, thus making conventional control systems operational and providing a more comfortable environment for the crew.

The University of California has independently undertaken the task of actually constructing a full-scale, manned ecological system patterned after the microterella. The system will be completed in early 1968. In it two men will be completely isolated from the outside environment and will be supported by the system described in simulated voyages of increasing durations. Microbiological regeneration of the men's wastes into oxygen and potable water will be studied in detail as will the men's nutritional and other physiological and psychological requirements. Results of studies which will be made with this closed regenerative system will be highly pertinent to long-term life support in lunar bases or in permanently manned orbiting stations.

8. SUMMARY AND CONCLUSIONS

8.1 Microterella

During the third year of the contract period, an algatron was installed in the microterella and suitable adaptations were made to accommodate for the necessarily high degree of miniaturization made in fitting the algatron in the unit. Experiments performed with the use of the modified microterella involved the effects of variations in amount and manner of illumination, length of detention period, and concentration of urea additive on algal yield. The permissible urea dosage was found to be less with the algatron system (100-150 mg/l of medium) than it was with a conventional batch-type culture (250-300 mg/l of medium). A maximum yield of 2.8 g/liter-day was attained at a detention period of 0.75 day, urea dosage at 100 mg/l of medium. This maximum yield was 12% greater than that obtained with the batch-type of culture system. In addition to the genetic factors, light apparently was the limiting factor in the study, since the algal concentration of the culture was almost the same at 0.75- and 1-day detention period; the yield, of course, was lower for the latter period.

8.2 Algae Nutrient Removal

Two algatrons, 4 ft high and 18 in. in diameter, were used in the experiments on algae nutrient removal. Approximately [illegible] of the incoming

total nitrogen, 85% of the NH_3-N, 30% of the phosphate, 40-72% of the calcium, and none of the magnesium were removed from the incoming medium at a daily input rate equivalent to that of the culture volume and a liquid output of about two-fifths of the culture volume. Three-fifths of the incoming liquid was lost by way of evaporation.

8.3 Waste Treatment

The study on waste treatment involved the use of two systems. In one the solid wastes received pretreatment in a specialized treatment unit before discharge into an algatron for additional processing. In the second, the solid wastes were discharged into the algatron without pretreatment, except for being ground in a Waring blender.

a. Pretreatment - Algatron Arrangement. The pretreatment unit consisted of a component whose successful function depended upon the difference in settling characteristics between algal cells and those of activated sludge. At a loading of 2.1 g feces (dry weight) and 74 ml urine/liter-day (BOD from 875 to 1061 mg/l), effluents were produced that had a BOD as low as 15 mg/l. Algal concentration ranged from 975 to 1475 mg/l. Operational difficulties encountered in the study originated in the tendency of the recirculation probe and connecting tubing to clog; and in the carryover of fecal and of bacterial floc particles from the pretreatment unit to the algatron.

b. Direct Injection of Solid Wastes. The second system involved the application of the accelerated symbiotic biomass principle to the algatron system. The applied loading ranged from the equivalent of 18.5% to 66% of the fecal and urine output of a 75-kg (165 lb) male. The BOD of the influent ranged from 242 mg/l at the lowest loading to 810 mg/l at the highest. The BOD of the effluent ranged from 14 mg/l at the lowest loading to 79 mg/l at the highest. Influent nitrogen (Kjeldahl nitrogen) ranged from 146 mg/l to a maximum of 450 mg/l. Effluent nitrogen ranged from 55 mg/l at the lowest loading to 152 mg/l at the highest. Influent phosphate loading ranged from 58 mg/l to 146 mg/l. Effluent concentration of phosphate ranged from 31 mg/l (lowest loading) to 79 mg/l (highest loading). On the basis of the results, from 0.038 to 0.155 sq meter of drum wall area would be needed per kilogram of body weight to treat body wastes to the extent generally required in terrestrial applications.

c. Water Regeneration. Water evaporation rates were measured regularly. The evaporated water may be condensed and used to meet the water requirements of the crew of a space vehicle; inasmuch as it is a low temperature distilled water, it is free from the objectionable distillates that would be present in water produced by conventional high temperature distillation of untreated wastes. During a three-month period of observation, the rate was 1.6 liters/liter of culture volume, or 17.3 liters/sq meter of culture surface. The high rate of regeneration obtained in the experiments indicates that this function can be easily carried on in an integrated system.

8.4 Design Considerations

The design of an integrated biological system for treating wastes of a "standard" astronaut is presented. The system consists of a number of algatrons divided into several series each with two algatrons acting in tandem. The total number of series per astronaut would be dependent upon the functional efficiency of the pairs of algatrons. The astronauts' wastes after being homogenized in waste water are applied to the primary algatrons for initial treatment and preoxidation. Effluent from the primary algatrons are passed to the secondary algatrons for further treatment. Effluent from the secondary algatrons can be used in homogenizing the astronauts' wastes for application to the primary algatron, or can be evaporated to produce water and dry solids. The latter can be stored or can be subjected to further decomposition. Sufficient low temperature distilled water to meet all of the astronauts' water requirements would be produced as a result of evaporation from the algatron cultures. Storage as well as treatment would be entirely odorless functions in the system as designed.

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13. ABSTRACT

The report describes experiments concerned with the effect of various environmental factors on removal of algal nutrients, degree of waste treatment, and extent of water regeneration accomplished with the use of an algal-bacterial culture grown in a mechanically rotated culture vessel (algatron). It also describes size and operational characteristics for a two-man environmental chamber, presents a design to support two men, and outlines basic characteristics for larger chambers in a space environment. The highest daily yield of algae was 2.8 g (dry wt)/l of culture. Total-N removal ranged from 70% to 90%; NH_3-N, 55% to 99%; PO_4, 30% to 80%; Ca, 17% to 70%; and Mg, 9% to 13%. Effluent BOD ranged from 14 mg/l at a BOD loading of 242 mg/l/day to 79 mg/l/day at 810 mg/l. From 87% to 91% of incoming volatile solids were stabilized at detention periods from 0.25 day to 1 day. Rate of evaporation (therefore, water recovery) ranged from 1.33 ml/sq meter/min at a relative humidity of 80% to 11.3 ml/sq meter at 45% relative humidity. According to the research findings for solid and liquid waste treatment, approximately 0.038 sq meter of drum wall area are needed per kg of body weight.

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Algae Culture	8	1				
Waste Treatment	8	1				
Water Recovery	8	1				
Stabilization	8	1				
Nutrient Removal	8	2				
Organic Destruction	8	1				
Growth Unit Design	8.2	1				
Heat Transfer	8.2	2				
Energy Transformation	8.2	2				
Detention Period	5	1				
Light Intensity	5	1				

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